SCHOOL OF CIVIL ENGINEERING

JOINT HIGHWAY RESEARCH PROJECT

JHRP-77-21

THE SEISMICITY OF INDIANA AND ITS RELATIONSHIP TO CIVIL ENGINEERING STRUCTURES — PHASE B

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PURDUE UNIVERSITY
NDIANA STATE HIGHWAY COMMISSION

Interim Report

THE SEISMICITY OF INDIANA AND ITS RELATIONSHIP TO CIVIL ENGINEERING STRUCTURES - PHASE B

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

December 21, 1977

Project: C-36-30B

File: 9-4-2

The attached Interim Report on the special research project sponsored by the Indiana State Highway Commission and the Administrative Building Council and titled "The Seismicity of Indiana and Its Relationship to Civil Engineering Structures - Phase B" is submitted as partial fulfillment of the objectives of the Study. Specifically the Report fulfills the requirements of Tasks 1 through 5 of the approved work plan for the Study.

The principal investigator, William D. Kovacs, has experienced time and personnel difficulties in conducting the research. He is also on leave of absence during the present year and until the Fall of 1978. A major investigator, Mr. William J. Murphy, returned to engineering practice before the Study was complete but continued to prepare a report of his work on this study while at Purdue. He and Professor Kovacs are the authors of the attached.

A total of 12 Tasks have resulted from the research and only the first five are covered herein. The following plan covers the completion of the Study - conduct of the following remaining tasks:

6. Site Response
7. Response Spectra-Time History
8. Microzonation Studies
9. Building Code Review
10. Specific Conditions-Hwys, Bridges
11. Specific Conditions-Bldgs.
12. Final Report

Work on Tasks 6 and 7 has almost been completed during previous periods. A decision was made to concentrate on Vanderburg County, specifically the city of Evansville, Indiana due to its population and proximity to seismic sources. Letters were written to organizations requesting information on boring logs to <u>bedrock</u>. Once obtained, the investigators assigned dynamic soil properties to the various layers of several <u>typical</u> soil sites in Evansville in order to compute the <u>ground</u> response. To accomplish this analysis, it was first necessary to establish a time-history of acceleration from the various potential seismic sources (they are discussed in Part II of the report). Three separate artificial earthquake accelograms have been generated. They are used as the input base rock motion for the response analysis. The response analysis will be completed upon return of Professor Kovacs in the Fall of 1978. This will complete Tasks 6 and 7.

Based on results of Tasks 6 and 7, existing surficial geological maps will be utilized to show expected engineering behavior as well as potential liquefaction zones in the areas of expected seismicity (Task 8). Task 8 will also be completed in the Fall 1978.

A million dollar study is now just being completed by the Applied Technology Council (ATC-3, sponsored by the National Science Foundation and the National Bureau of Standards). This study is primarily concerned with the seismic design of building structures and utilizes a new seismic lateral force equation based on site variables as well as structural variables. In the last two years, several research reports dealing with the seismic design of bridges as well as bridge retro-fitting have been published. These studies will be heavily drawn upon to complete Tasks 9 and 10. Likewise, other reports plus ATC-3 will be used to complete Task 11.

It is planned to complete a draft Final Report by the end of December, 1978, with final copy completed by March 31, 1979. It is anticipated that many graphs, photos, etc. will be required to complete Parts III and IV. The funds still remaining in the Study account are expected to be sufficient to complete the Study as indicated.

The attached Report is submitted to the ISHC and the ABC for review, comment and acceptance as partial fulfillment of the Study as indicated.

Respectfully submitted,

Harold L. Michael

Harold L. Michael
Associate Director

HLM:ms

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Interim Report

THE SEISMICITY OF INDIANA AND ITS RELATIONSHIP TO CIVIL ENGINEERING STRUCTURES - PHASE B

Task 1 - Literature Survey
Task 2 - Seismic History
Task 3 - Regional Geology - Seismo-Tectonics
Task 4 - Probability and Statistics
Task 5 - Design Earthquakes

by

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Purdue University
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The authors gratefully acknowledge support from the Administrative Building Council of Indiana and the Indiana State Highway Commission for their financial support. The authors thank Professors Robert F. Blakely of Indiana University and the Indiana Geological Survey, Lawrence W. Braile of Purdue University and Otto W. Nuttli of St. Louis University for their critical review and comments of Tasks 1 through 5.

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PART I - TASKS 1, 2, AND 3

INTRODUCTION

GENERAL

In this Part I we present the results of Task 1 (Literature Study), Task 2 (Seismic History) and Task 3 (Geology Seismo-Tectonics) of the research study, "The Seismicity of Indiana and Its Relationship to Civil Engineering Structures-Phase B."

The findings of Phase A were presented to the JHRP Board on December 28, 1972 in Report Number 44.

The major conclusions of the 1972 report were that:

1. Indiana has a significant seismic history which is concentrated in the southwest part of the state.
2. We can expect continued seismic activity from at least two sources. A smaller earthquake of probable Richter magnitude 6 from the nearby Wabash River Fault system and a larger distant earthquake from the New Madrid (Missouri) Fault System with an expected Richter magnitude of 7.

Based on these conclusions it was recommended that:

1. Seismic provisions be incorporated into Indiana's Building Code for buildings and highway structures.
2. Existing bridges be retrofitted to prevent excessive movement during seismic loading.
3. Probability theory be used to establish factor of safety of structures taking into account the frequency of occurrence of earthquakes in the Indiana area.
4. Soil and geological conditions be taken into account in assigning seismic risk and loading.

Engineering Relevance

The State of Indiana has adopted the Uniform Building Code (UBC) with modifications. As of this writing, the seismic provision of the Adopted UBC have been omitted pending further study. The standard seismic provisions of the UBC place the northern half of the state in seismic risk zone 1; the southern half is in seismic risk zone 2 while the extreme southwest corner of the state is in seismic risk zone 3. These zones correspond to minor damage (primarily from distant earthquakes), moderate damage (Intensity VII, the threshold of structural damage), and major damage (Intensity VIII or higher), respectively.

The various seismic risk zones do not take into account the frequency of earthquake activity nor the local soil and geologic conditions which may tend to amplify the base rock motion through the upper soil layers. A need has been recognized to better define seismic areas within the State taking into account:

1. the frequency and size of expected earthquakes
2. the effects of local soil and geologic conditions on response
3. distance and direction from earthquake source
4. nature and purpose of land use and construction.

The purpose of the current study is to recommend seismic design provisions to be incorporated into the State building code as a modification to the provisions of the UBC.

The serious consideration being given to seismic provisions in the Indiana Building Code is more than justified when one considers that damage in the 1971 San Fernando earthquake, which was not a major earthquake in terms of its size, amounted to an estimated $500 million

loss to private and public property (Coffman and von Hake, 1973). A loss of $24 million resulted from damage to roads and bridges, as well as immeasurable losses from interruption to traffic flow including isolation of emergency facilities (Podolny and Cooper, 1974).

BASIC PRINCIPLES

Before discussing the regional earthquake and geologic environments, and the relationship between earthquakes and geology, we shall review some of the basic principles and nomenclature of earthquake engineering, to assist readers with non-technical backgrounds in this area. The Glossary, Appendix C, also is presented to define technical terms.

Figure 1 shows a cross-section through the earth. The epicenter, hypocenter or focus, focal depth, epicentral distance, and hypocentral distance are shown.

Figure 2 shows a plan of the earth's surface, again showing the epicenter, of a ficticious earthquake, and the epicentral distance to a site.

The felt effect of an earthquake at any point is the Intensity of the earthquake at that point. Intensities are reported in Roman numerals according to the Modified Mercalli Intensity Scale (Table 1). Intensities range from Intensity I (generally not felt) to Intensity XII (damage total). Thus it can be seen that several or many intensities may be reported for the same earthquake, depending on the distance from the epicenter and local conditions such as soil thickness or type of structure. It is often possible to construct isoseismals or lines defining the zone in which the earthquake was felt with generally the same intensity. Figure 3 shows isoseismals for an earthquake which had

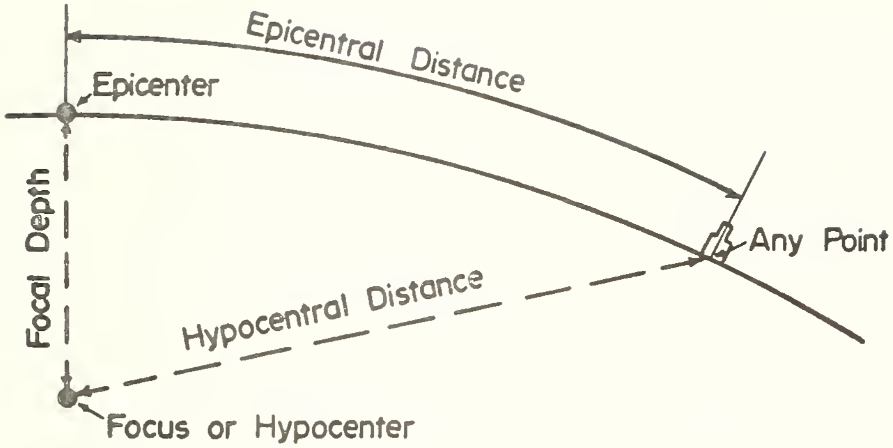


FIGURE I CROSS SECTION OF THE EARTH SURFACE; DEFINITIONS.

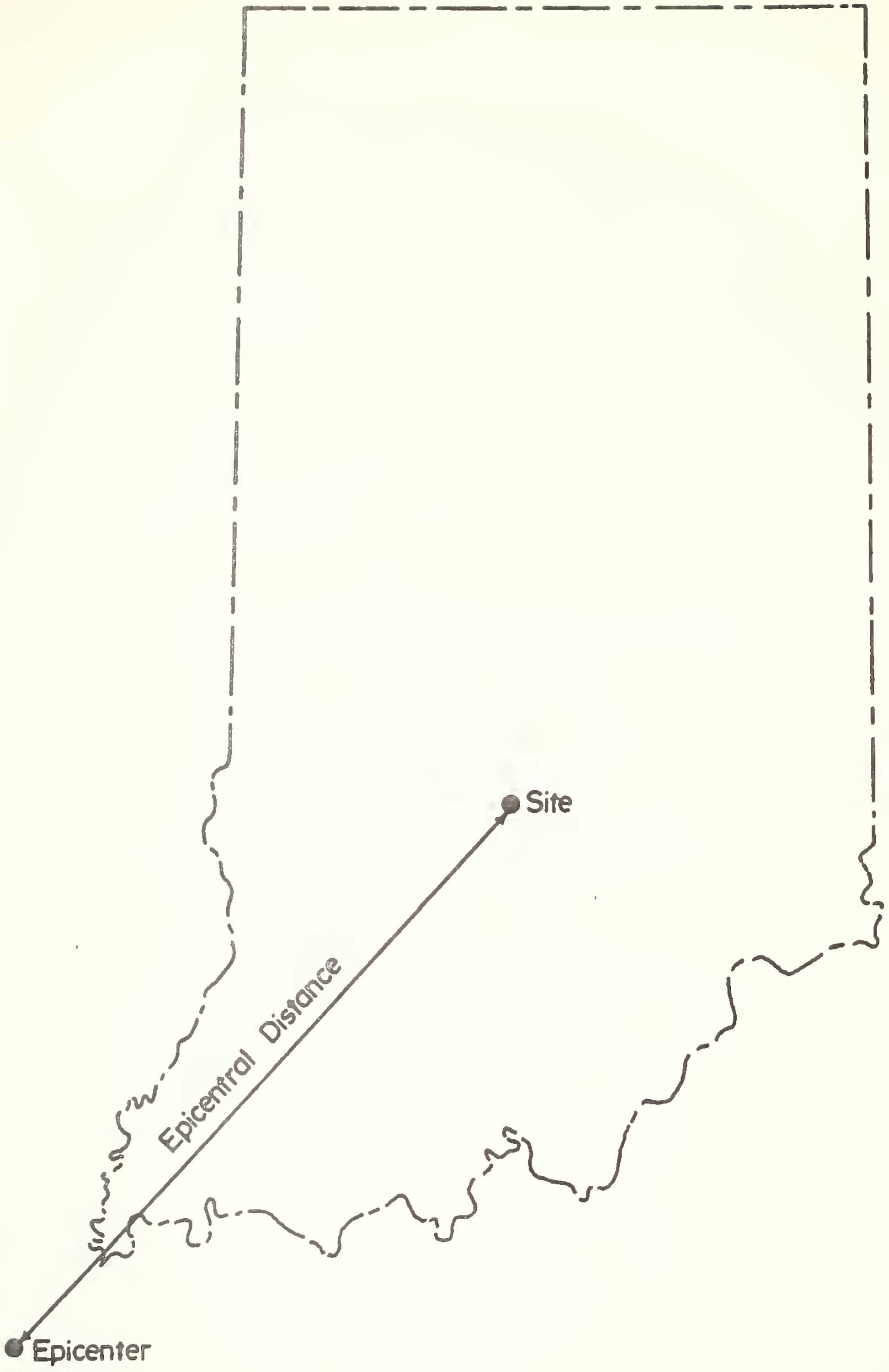


FIGURE 2 PLAN AREA OF EARTH SURFACE; DEFINITIONS.

TABLE 1

MODIFIED MERCALLI INTENSITY SCALE OF 1931

I. Not felt. Marginal and long-period of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors, Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frames crack.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, and so on, off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken visibly, or heard to rustle.

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornics, unbraced parapets, and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factor stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and walls. Cracks in wet ground and on steep slopes.

TABLE 1 (Cont'd)

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of slight and level distorted. Objects thrown into the air.

Construction Type

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connection with the conventional Class A, B, C construction).

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but no designed in detail to resist lateral forces.

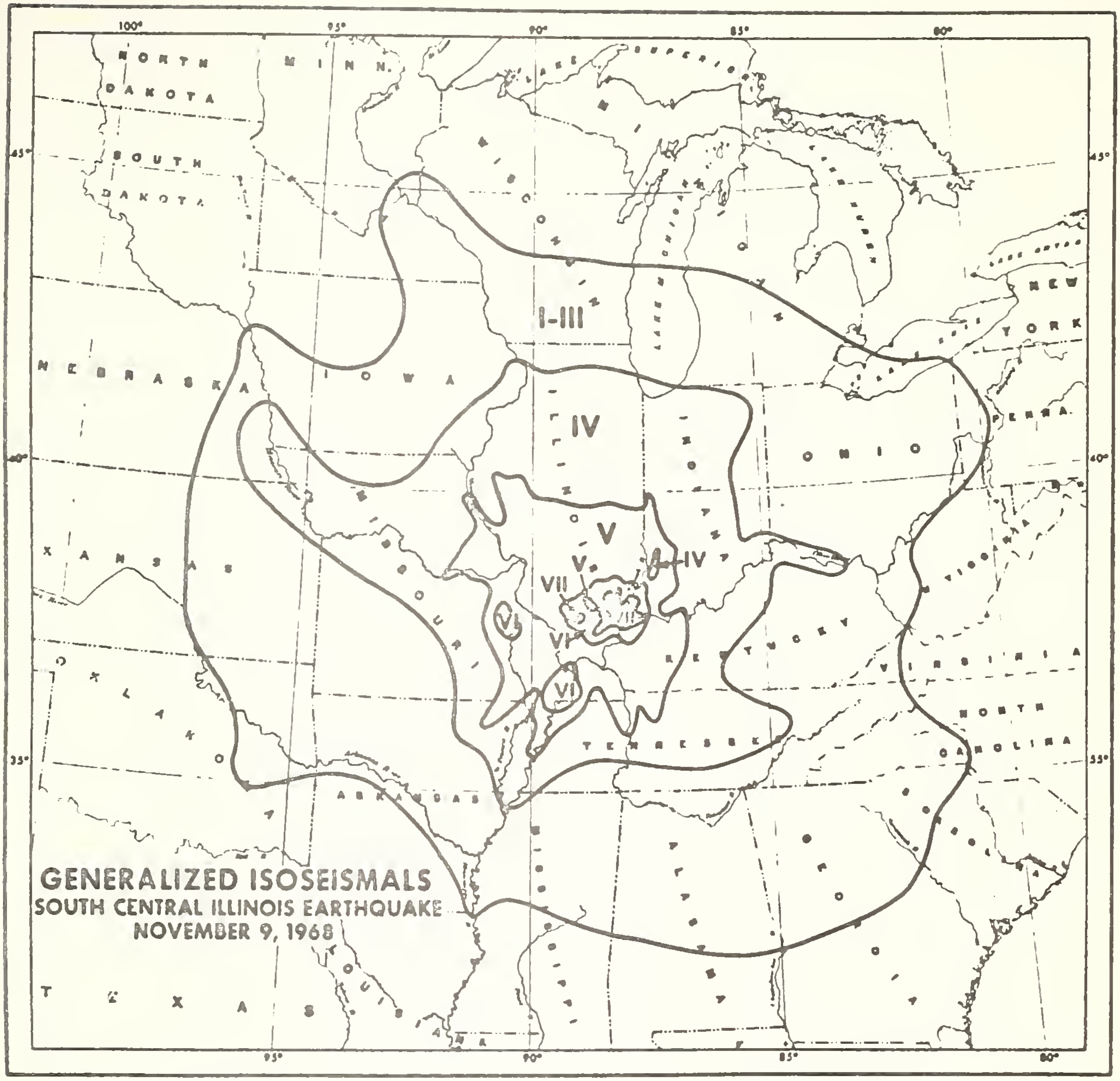
Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

a maximum intensity of VII near its epicenter. The isoseismal outside of which the earthquake was not felt is the limit of perceptibility. The area within this isoseismal is the felt area or area of perceptibility. Here the maximum intensity is VII and the intensity in, for example, north-central Indiana is IV.

Intensity V is often considered the threshold of intensity at which people are disturbed or frightened, and Intensity VII the threshold for structural damage to buildings, bridges, etc.

The magnitude of an earthquake is related to its energy release and is the closest we have come to defining the absolute size of a shock in a quantitative manner. Local or Richter magnitude, M_L, is a measured value equal to the logarithm of the pendulum displacement which would be expected in a standard type of seismograph if such a seismograph were located a distance of 100 kilometers from the epicenter. Magnitudes are reported on the Richter scale and have values of about 2 or 3 for the smallest felt shocks to greater than 8 for major earthquakes. The Richter scales were set up so that the smallest and largest earthquakes could be measured and a magnitude assigned to them. It is possible to have a negative magnitude earthquake, since a very small value for seismograph pendulum would have a negative logarithm. The Richter magnitude is restricted to epicentral distances less than 600 km. Two other magnitudes that will be used in this report include surface wave magnitude, M_S, and body wave magnitude, m_b. Both of these megnitudes are functions of the log of the ratio of the surface wave amplitude and body wave amplitude, respectively, and the epicentral distance. Richter magnitude is restricted to Southern California earthquakes from which it was derived.



(After Gordon et al, 1970)

Roman Numerals Refer To The Modified Mercalli Intensity Scale

FIGURE 3 GENERALIZED ISOSEISMAL MAP OF THE NOVEMBER 9, 1968 SOUTHCENTRAL ILLINOIS EARTHQUAKE.

REGIONAL EARTHQUAKE ENVIRONMENT

GENERAL

In the mind of the public, the central United States is not a region prone to earthquakes. Earthquakes of consequence, it is believed, are limited to the San Andreas fault region of California, and even more likely, to such far away places as Alaska and Japan.

On a worldwide basis, the interior continental masses do tend to be seismically stable. It is true that most earthquakes occur in well-defined seismic zones. These zones coincide with the limits of the major crustal plates described in the Plate Tectonic Theory (see, for example, Matthews, 1973 and Walper, 1976). However, local seismic zones exist within these crustal plates. In fact, no place on the globe can be said to be immune from seismic activity.

The seismic history of the north-central United States shows a regular and continuing pattern of earthquake activity from the arrival of the colonists to the present day. Even earlier activity is noted in the legends of the Indians and through topographic evidence. Some of these earthquakes can be related to specific geologic structure. Some activity, however, cannot yet be related to known geologic structure.

Seismic activity will continue in the Mid-west. In order for us to estimate appropriate earthquake design criteria, we must examine the seismic history in detail, and attempt to understand the relationship of this earthquake history to the geology of the region, to the degree possible. Earthquake occurrence is not a random process in time and space, but results from definite, albeit poorly understood, geologic

factors. As more instrumental data are obtained pinpointing the origins of earthquakes in the Midwest, we will better understand the relationship of these shocks to specific geologic features. In this we are handicapped by the lack of exposed fault scarps and zones with which to relate seismicity. Until then, we must make primary use of seismic history, in an attempt to establish patterns of earthquake occurrence. Statistical methods are applied to this historical record to predict future activity.

In examining the early history of earthquake occurrence in the eastern and Midwestern United States, it is clear that earthquakes have tended to "occur" where there were people to report them. This is mostly true of small earthquakes whose effect was limited to a small geologic region. If no one was in the area to report, the shock went unrecorded. This is also part of the reason why earthquake reports tended to be concentrated in river valleys, where most of the population centers existed. River valleys also tend to amplify earthquake motion. Thus a small or distant earthquake may have only been felt at locations with poor ground conditions such as soft soil (unconsolidated sediments) which tends to amplify the base rock acceleration. The ground acceleration may be several times the base rock acceleration.

Larger earthquakes, which were felt over larger areas and left physical evidence, have been generally adequately reported. However, in the case of some of the older and especially smaller earthquakes, the location and Intensity may be approximate. In our studies, the total historical record is used to establish the largest size earthquakes to be expected in a region. The largest earthquake can only be estimated

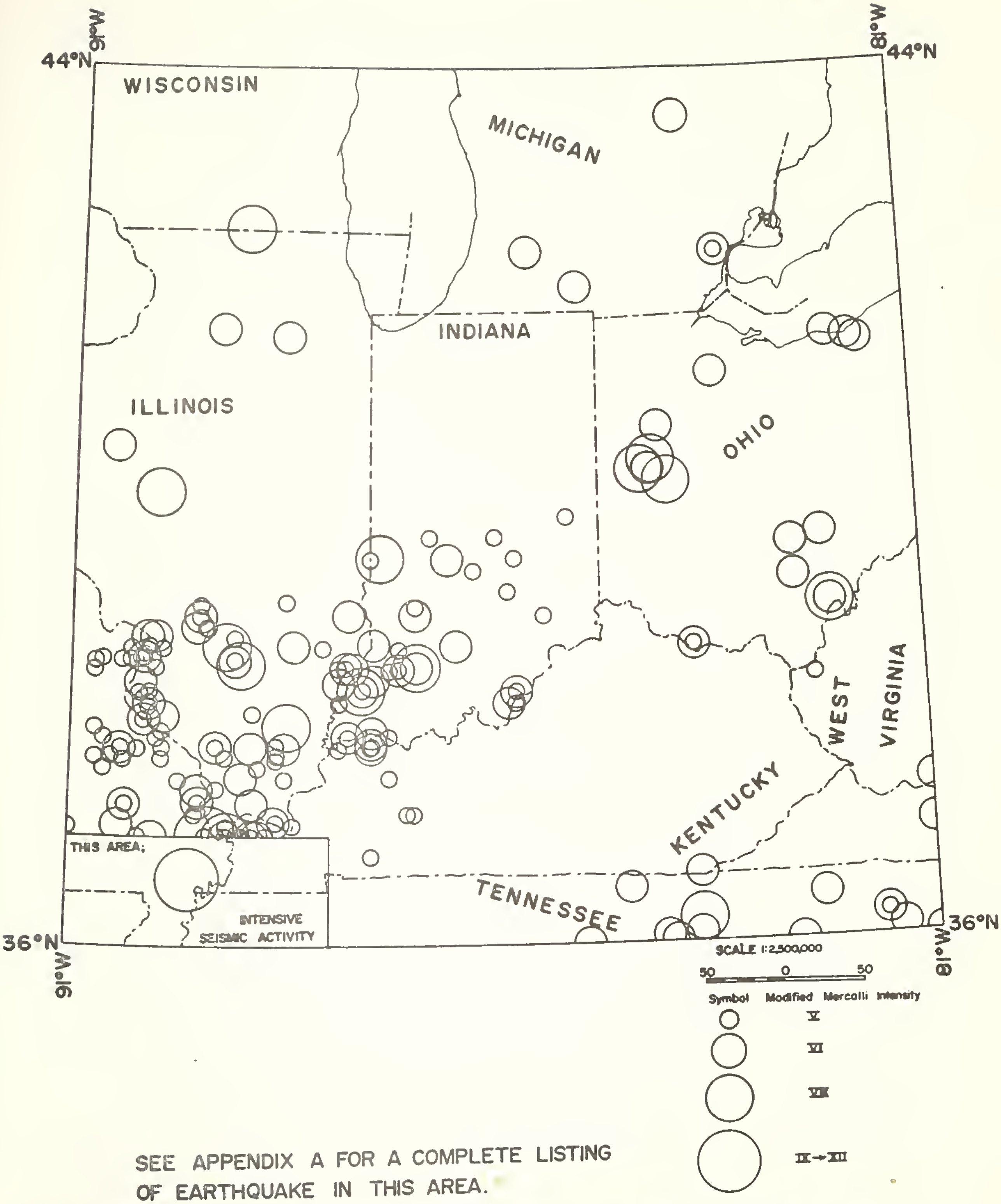
based on previous seismic history. There is not, however, 100% assurance that the historic record as we know it is a complete and accurate reflection of past seismicity. Frequency of occurrence and statistical studies make use of the more recent seismic history. In recent years, sensitive instruments insure that almost no earthquake of $m_b > 4$ goes unnoticed.

REGIONAL SEISMIC HISTORY

In this study, we have defined the "region" as that area bounded by the Coordinates, Latitude 36°N to 44°N and Longitude 81°W to 91°W, as shown on Figure 4. In an examination of the seismic history of the region, a list of over 500 earthquakes was prepared. These earthquakes are listed in Appendix A with their epicenters shown in Figure 4. Almost all were felt, although some of the smallest are known by instrumental record only. Many caused damage or concern to the public.

The earliest earthquake report in the region was a "violent" shock in the Muskingum River Valley of Ohio in the summer of 1776. It is reported that the shock was so violent that furniture was nearly overthrown; people and animals were frightened. The shock was accompanied by a rumbling noise and is said to have lasted 2 to 3 minutes. There were similar shocks in the nineties and in the first decade of the following century. These caused the Indians to predict a great earthquake, the prediction being based on the Indian tradition of an earthquake at an earlier time. The geological evidence confirms this, but the date cannot be fixed. [Coffman and Von Hake (1973)].

The earthquake history of the region is dominated by a series of earthquakes which occurred in southeastern Missouri and northwestern



SEE APPENDIX A FOR A COMPLETE LISTING OF EARTHQUAKE IN THIS AREA.

FIGURE 4 REGIONAL EPICENTER MAP.

Arkansas in 1811 and 1812. These are known collectively as the New Madrid Series. Three major shocks occurred on December 16, 1811, January 23, 1812, and February 7, 1812. Each was followed by a series of aftershocks. The total number of shocks in the series during the period from December 16, 1811 to March 15, 1812 amounted to over 100 moderate or strong shocks, and hundreds of smaller shocks. (Nuttli, 1973b). The aftershocks lasted throughout at least 2 years. Nuttli has assigned body wave magnitudes of 7.2, 7.1 and 7.4 to the major shocks, respectively (Nuttli, 1973b). The corresponding surface wave magnitudes, M_S, were likely to be 8.0, 7.9, and 8.2, respectively. The shocks were felt over an area of about 2,000,000 square miles and caused marked topographic changes in the epicentral region. In terms of their magnitudes, widespread area of perceptibility and the damage and topographic changes in the epicentral region, these shocks are considered by some to be the largest to have occurred in North America in modern history (Richter, 1958).

A detailed description of the New Madrid Series of earthquakes is presented in Appendix A.

Several other strong earthquakes have occurred along a lineament trending northeast through New Madrid. An earthquake near Charleston, Missouri in 1895 was the severest shock in central United States since the 1811-1812 series. The shock had a maximum intensity of VIII and was felt in 23 states (Gordon et al, 1970).

These and other stronger earthquakes of the New Madrid Seismic Zone (1869-1968) are listed in Table 2. The New Madrid Seismic Zone will be discussed in a later section.

The most recent of these larger shocks, that of November 9, 1968 which occurred in central west Illinois is the largest in the region

since 1895. It had a maximum intensity of VII and was felt in an area of 580,000 square miles, covering all or part of 23 states. Some damage occurred near the epicenter, consisting of downed chimneys, cracks in foundations, overturned tombstones, and scattered instances of collapsed parapets. Minor damage was caused at Evansville, 50 miles to the east, and St. Louis, 110 miles northwest. The earthquake caused alarm at Chicago, over 270 miles to the north.

This shock is important in that it clearly demonstrates the ongoing nature of significant earthquake occurrence in the mid-continent. The felt effect of this earthquake is illustrated on the isoseismal map, Figure 3. Besides isolated pockets of higher or lower Intensity within a given contour interval, a given Intensity contour appears to follow up the major river valleys. This aspect is significant because the river valleys contain soft unconsolidated sediments which tend to be amplified by the underlying base rock acceleration, as compared to other locations at the same epicentral distance. The actual amplification would vary from location to location depending on spacial geometry and topography of the site (Kovacs, et al, 1971).

To the east of Indiana, there is a history of moderate earthquake activity in west-central Ohio. Shocks as large as Intensity VII-VIII have been reported, while there have been numerous smaller shocks. The larger of these shocks were strongly felt in Indiana.

EARTHQUAKE HISTORY IN INDIANA

Earthquakes which have affected Indiana include several of the larger regional earthquakes described in the previous section, as well as occasional smaller shocks with their epicenters within the state.

TABLE 2

STRONGER EARTHQUAKES IN THE NEW MADRID SEISMIC ZONE: 1869-1968

Year	Locality	Lat. °N	Long. °W	Felt Area (sq. mi.)	Intensity(MM)
1895	Charleston, Missouri	37.0	89.4	1,000,000	VIII
1909	Indiana-Illinois Border	39.0	87.7	30,000	VII
1923	Marked Tree, Arkansas	35.5	90.3	40,000	VII
1927	Western Tennessee and Arkansas	36.5	89.0	130,000	VII
1934	Rodney, Missouri	37.0	89.2	28,000	VII
1965	Southwestern Illinois	37.1	89.1		VII
1968	South-central Illinois	38.0	88.5	580,000	VII

(after Gordon et al 1970)

According to the Catalog of Coffman and Von Hake (1973), only twelve earthquakes of Intensity V or greater have originated within the state. These are listed in Table 3. The largest of these was Intensity VII. In addition, smaller earthquakes have been recorded, and are listed in Appendix A. These smaller shocks are of interest in that they point to the potential for future earthquake activity.

The most damaging earthquake and the only Intensity VII shock originating within the state occurred on September 27, 1909 near the Illinois border between Vincennes and Terre Haute. Some chimneys fell, several building walls were cracked, light connections were severed and pictures were shaken off the walls. It was strong in Indianapolis and Oakland City. It was felt in an area of 30,000 square miles including the southwestern half of Indiana, all of Illinois and parts of Iowa, Kentucky, Missouri, Arkansas and possibly in parts of Kansas.

The only other damaging earthquake originating in Indiana occurred on April 29, 1899 and rated Intensity VI to VII on the Modified Mercalli Scale. It was strongest at Jeffersonville and Shelbyville, and at Vincennes chimneys were thrown down and walls cracked. It was felt in an area of 40,000 square miles.

Of the shocks originating outside of Indiana but affecting the state the worst (except perhaps for the 1811-1812 New Madrid Series) was that of November 9, 1968 in southern Illinois. The regional effect of this shock is described in the previous section.

In Indiana, damage was reported or the shock was strongly felt in communities in the counties of Gibson, Knox, Martin, Pike, Posey, Spencer, Sullivan, Vanderburgh, and Vigo (US Earthquakes, 1968, Gordon et al, 1970).

According to the records of [illegible] and [illegible] only twelve earthquakes of intensity [illegible] the state. Three were [illegible] intensity VII [illegible] and [illegible]

[illegible]

TABLE 3

EARTHQUAKES ORIGINATING WITHIN INDIANA

(Intensity V or greater)*

Date	Locality	Intensity	Felt Area (square miles)
1827 Aug. 6	New Albany	VI	-
1827 Aug. 7	New Albany	VI	-
1876 Sept. 25	Evansville	VI	60,000
1887 Feb. 6	Vincennes	V-VI	75,000
1891 July 26	Evansville	V-VI	-
1899 Apr. 29	SW Indiana	VI-VII	40,000
1906 May 11	SW Indiana	IV-V	800
1907 Jan. 29	Morgan County	V	-
1909 Sept. 27 (2 shocks)	SW Indiana	V	30,000
1919 May 25	Southern Indiana	V	18,000
1925 Apr. 26	SW Indiana	V	100,000
1931 Jan. 5	Elliston	V	500
1938 Feb. 12	Porter County	V	6,600
1958 Nov. 7	SW Indiana	VI	33,000
1976 Apr. 8	Stinesville	V	-

*A complete listing is given by Blakely and Varma, 1976.

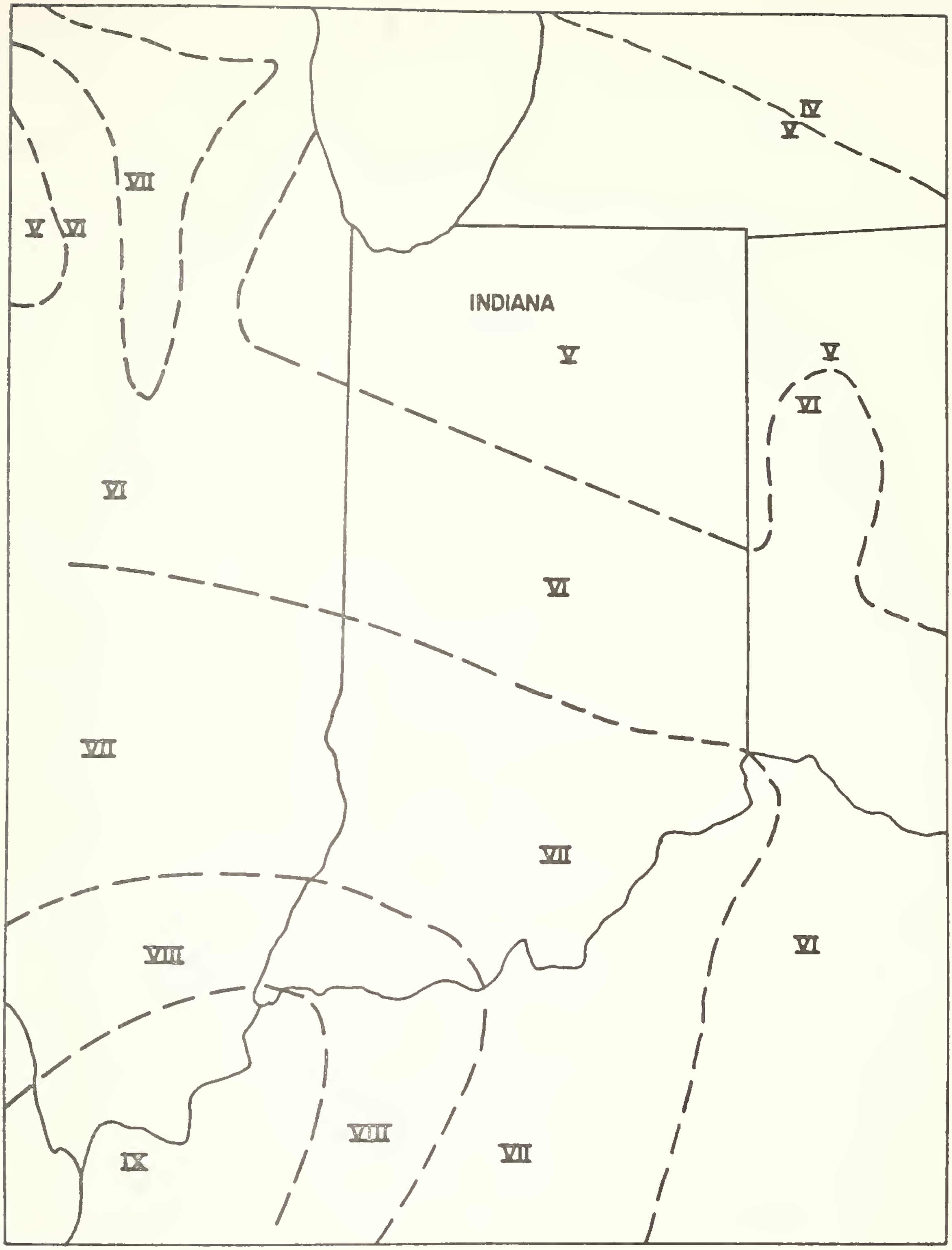
Intensity VII was reported from Cynthiana where chimneys were cracked, twisted and toppled; at Fort Branch, where groceries fell from shelves and a loud roaring noise was heard, and at Mount Vernon, New Harmony, Petersburg, Princeton, and Stewartsville, all of which had similar effects. At Poseyville, "Fish jumped out of the rivers, ponds and lakes".

Almost exactly ten years earlier on November 7, 1958, an earthquake originating near Mt. Carmel, Illinois, caused plaster to fall at Fort Branch. Roaring and whistling noises were heard at Central City and the residents of Evansville thought there had been an explosion or plane crash. It was felt over 33,000 square miles of Illinois, Indiana, Missouri and Kentucky.

On March 2, 1937 a shock centering near Anna, Ohio threw objects from shelves at Fort Wayne and some plaster fell. Plaster was also cracked at Indianapolis. Six days later, another shock originating at Anna brought pictures crashing down and cracked plaster in Fort Wayne and was strongly felt at Lafayette. (Lander, 1972).

When isoseismal maps for the principal historical earthquakes are superimposed upon one another, a map of maximum historical Intensity can be obtained for the Indiana area. Such a map is presented on Figure 5. In general the maximum past or historical Intensity increases downward to the south west part of the state from Intensity V to Intensity VIII at the junction of the Wabash and Ohio Rivers.

In this section we have briefly reviewed the earthquake events considered to be of most interest in defining the seismic environment in Indiana. In the next section, we will examine the regional geologic environment and its relationship to earthquake occurrence in the Midwest.



(AFTER KOVACS, 1972)

1:2,500,000

10 0 50miles 100 miles

Roman Numerals Refer to the Modified Mercalli Scale of 1931

FIGURE 5 MAXIMUM HISTORICAL INTENSITY MAP OF INDIANA - 1811 TO DATE.

REGIONAL GEOLOGIC ENVIRONMENT

GENERAL

Comparing a plot of worldwide earthquake distribution with a corresponding relief map will clearly show a general correlation between epicentral concentrations and areas of high relief and large scale tectonic activity.

Evidence of faulting may indicate a relative structural weakness in an area. Since adjustment will probably occur in an area of structural weakness, seismic activity might be expected to be more prevalent in a faulted area than in an undisturbed area.

The relationship between faulting and earthquakes is complex and not too well understood by seismologists. Most authorities accept that faulting causes the earthquake; the earthquake does not cause the faulting (Richter, 1958).

Krinitzsky (1974) discusses in detail the relationship between faulting and earthquake occurrence. This work is recommended as a summary of the state of knowledge concerning the significance of faulting in an earthquake study. We will examine the geology of the region and attempt to relate earthquake occurrence to known or suspected geologic structures. In many cases this will be possible. However, in some areas within the region, insufficient knowledge of geologic structure exists to permit a correlation. An active surface trace is not required inasmuch as earthquakes originate at great depths. A fault may tend to be active at depth without surface evidence. Such appears to be the case with the New Madrid, Missouri area. In such cases, until more data become available, these areas must be defined on the basis of the epicenter pattern alone.

Before examining specific geologic structures, let us examine the landforms or physiography of the region as a clue to what may lie below.

Physiography

Physiography is the science dealing with the description of landforms. These landforms are described in terms of attitude, relief and type of landform present. The landforms are due to the combined interaction of geomorphic processes acting over a period of time and under a particular historical climatic environment on a distinct type or set of parent material types each with its own unique geologic structure.

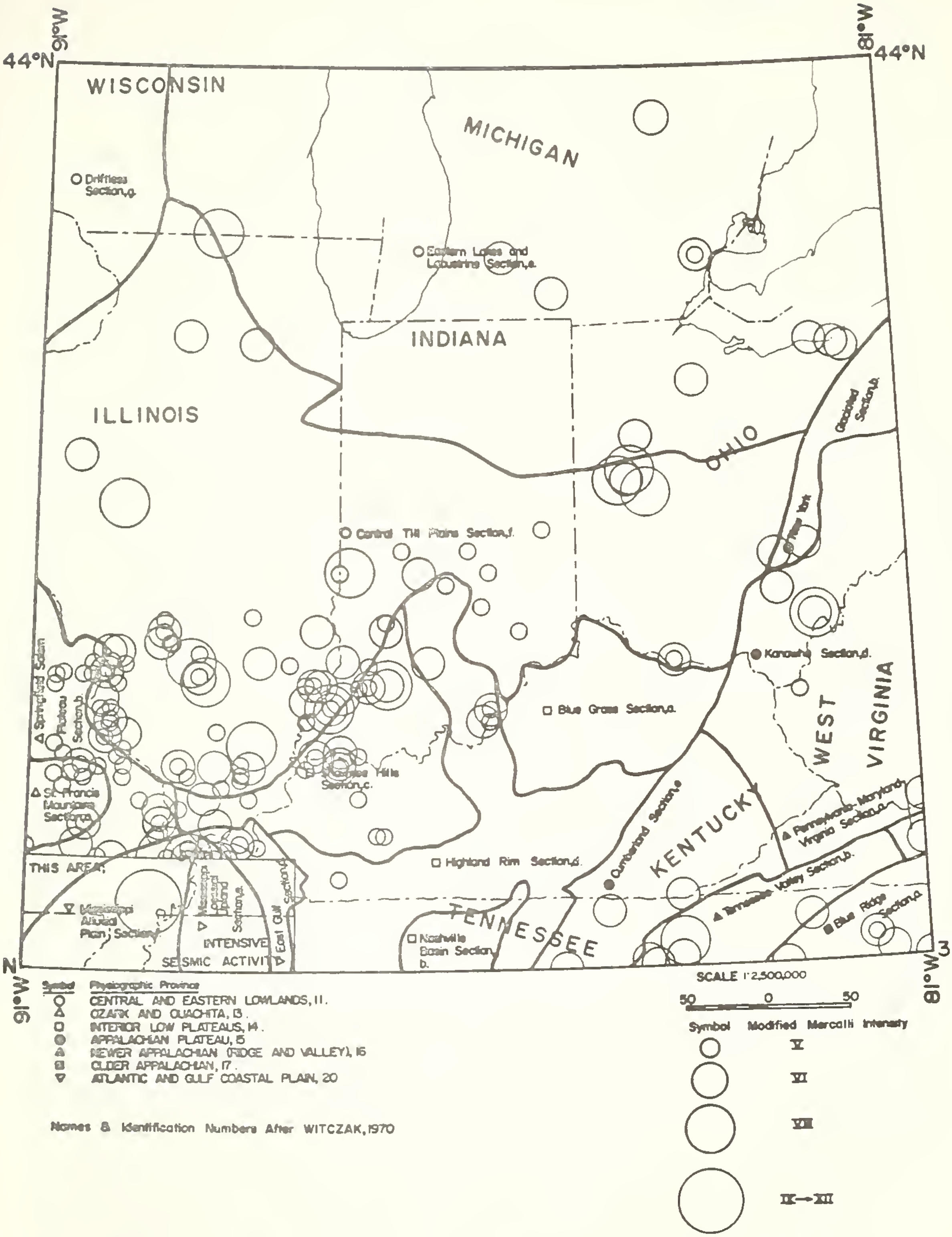
A regional physiographic unit attempts to delineate an area possessing a unique or repetitive series of landforms. In general (but not always) regional physiographic units possess a unique type or repetitive types of parent material and geologic conditions (Witczak 1970). Thus, a consideration of the regional physiographic units is useful in a first attempt at zoning the region with respect to the geologic factors which may be related to earthquake occurrence or effect.

The major physiographic units in the region are shown on Figure 6. This plate is based on the work of Witczak (1970). For a description of the physiographic units, the reader is referred to the principal references on regional geomorphology, for example, Thornbury (1965). The physiography of Indiana is discussed in the section on Indiana Geology, and in Appendix B.

Tectonic Features

General:

The Central Stable Region of the United States, within which Indiana is located, is underlain by Precambian crystalline rock beneath varying



Names & Identification Numbers After WITCZAK, 1970

FIGURE 6 REGIONAL PHYSIOGRAPHY.

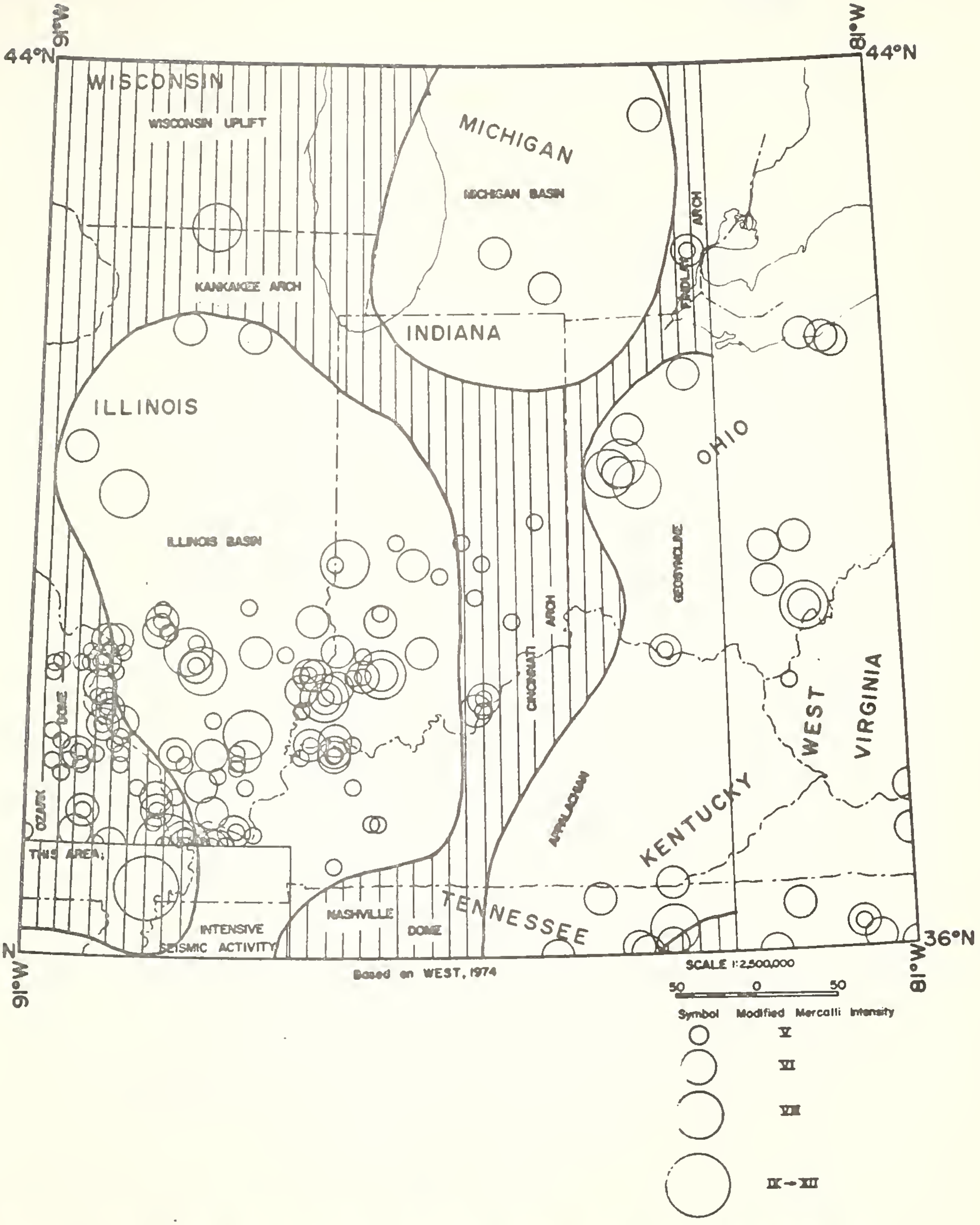
thicknesses of younger sedimentary rock. The crystalline basement rock forms the overall structural framework for the overlying sedimentary strata (Frey and Lane, 1966).

The pattern of the tectonic environment is established by several major basin or synclinal structures connected by arches or domes. There are several fault systems within the region, as well as isolated faults which often are related to these arch structures. The basin and arch structural system is shown on Figure 7 (West, 1974). The faults and fault systems are added to form the Tectonic Map on Figure 8 (Cohee, et al, 1962, Hadley and Devine, 1974).

Basin and Arch System:

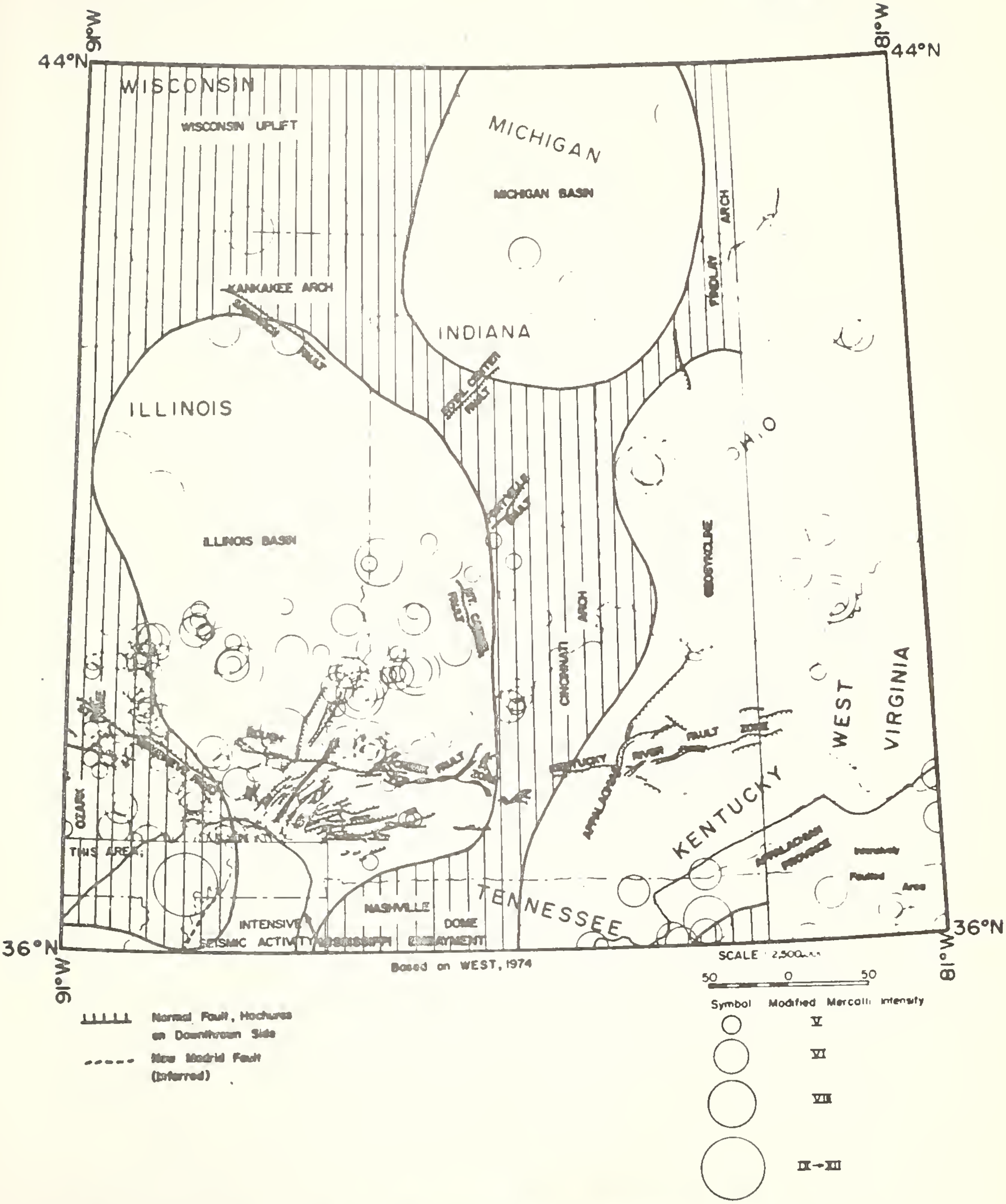
The formation of the basin and arch system began at the end of the Paleozoic Era. There have been subsequent periods of uplift, erosion, and repeated uplift. At the present time, these processes appear to be mostly dormant, with the exception of the Mississippi Embayment. Topographic evidence within the Mississippi Embayment suggests that Tectonic activity is currently taking place. These topographic changes at the ground surface reflect displacements that are taking place at great depth, probably in basement rock, up to ten miles below the surface (Krinitzsky, 1972, Snyder, 1968).

With regard to Indiana, the major regional basin structures are: The Michigan Basin, which occupies much of Michigan and part of northern Indiana; the Appalachian Geosyncline which trends north-south through central Ohio and Kentucky; and the Illinois Basin which occupies much of Illinois and part of western Indiana. The northern limit of the Mississippi Embayment approaches the southern part of the Illinois Basin.



Based on WEST, 1974

FIGURE 7 BASIN AND ARCH SYSTEMS.



Based on WEST, 1974

FIGURE 8 REGIONAL TECTONIC MAP.

These basins are separated by arch or dome structures. The northwest-southeast trending Kankakee Arch separates the Michigan and Illinois Basins. The Cincinnati Arch, trending north-south, separates the Appalachian Geosyncline and the Illinois Basin. The Nashville Dome separates the Appalachian Geosyncline in Kentucky from the Illinois Basin and northern Mississippi Embayment.

Sterns and Wilson (1972) have postulated an arch structure which they call the Pascola Arch trending northwest-southeast and separating the Illinois Basin from the Mississippi Embayment. The Pascola Arch is discussed in more detail in a later section dealing with earthquake relationships. The structure is believed to be part of the Ozark uplift, connecting that structure with the Nashville Dome (M & H Engineering, 1973).

Fault Systems:

The principal fault systems in the region of study are:

- Mississippi Valley Fault Zone
- St. Genevieve - Cottage Grove - Shawneetown - Rough Creek Fault System
- Wabash Valley Fault System

1. Mississippi Valley Fault Zone

In his classic report of the New Madrid earthquake of 1811-1812, Fuller (1912) suggests that the earthquake epicenters were located along a northeast-southwest trending fault about 15 miles west of the Mississippi River at New Madrid. Mateker (1968) suggests the existence of a major fault which may correspond to that proposed by Fuller (Nuttli, 1973b).

Other investigators (McGinnis, 1963) have placed this fault or a second parallel fault along the trend of the Mississippi near the town

of New Madrid. According to Heinrich (1949) the middle Mississippi Valley represents a structural trough between the Ozark Uplift and the Cincinnati Arch. This suggests the existence of a northeast-trending fault forming the southeast boundary of the subsidence block occupying the valley (Gordon et al, 1970). The fault zone roughly parallels the trend of the Mississippi River.

Stearns & Wilson (1972) describe the New Madrid fault system as extending more than 200 miles southwestward from Vincennes, Indiana, through southeastern Illinois, southeastern Missouri, and into northeastern Arkansas. They comment that the possible extension of the New Madrid Faulted Belt to the north and northeast was beyond the limits of their study, and therefore not specified. Krinitzsky (1972) feels that the New Madrid Fault does not exist north of the Cottage Grove and Rough Creek fault zone.

2. St. Genevieve - Cottage Grove - Shawneetown - Rough Creek Fault System

The Shawneetown-Rough Creek Fault Zone is composed of high angle faults. It has a maximum vertical displacement of 3000 feet or more. The east branch of this fault extends across Kentucky into West Virginia. In the southeastern corner of Illinois south of this fault zone is the area of intense faulting where most of the major faults trend southwest-northeast. The trace of the Rough Creek and major northeast striking faults intersect near Eldorado, Illinois, approximately 11 miles south of the instrumental epicenter of the 1968 earthquake. Little seismicity has been associated with the eastern branch of the Rough Creek fault which extends across Kentucky into West Virginia.

The St. Genevieve fault system strikes northwest and forms the boundary between the Illinois Basin and Ozark Uplift. Displacement of basement rocks along the fault indicates vertical movement exceeding 2,000 feet.

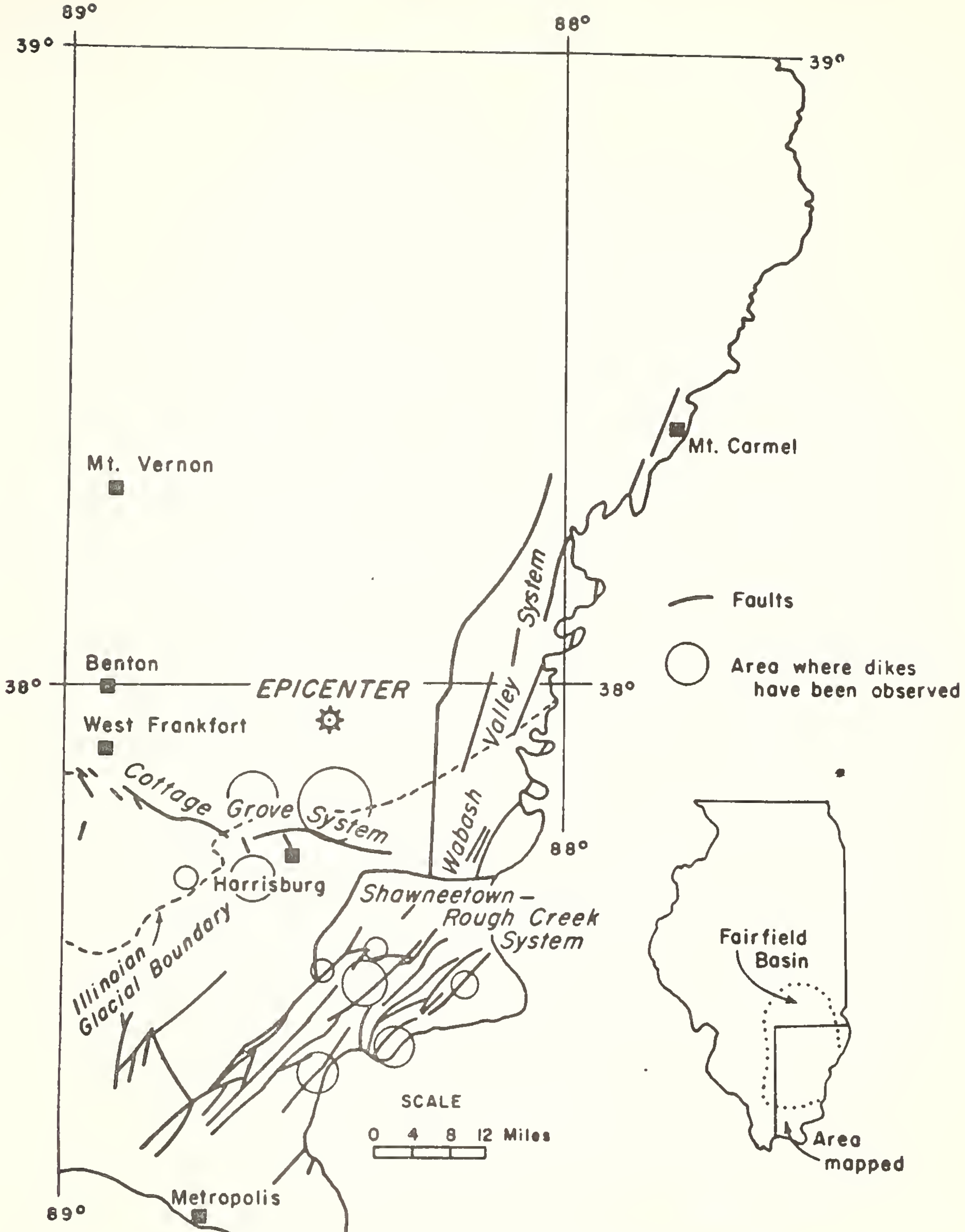
The Cottage Grove System consists of high angle faults with less displacement than the Rough Creek Fault. The above mentioned fault systems are shown in Figure 9, after Heigold (1968). Also shown on this figure is the epicenter of the November 9, 1968 South Central Illinois Earthquake.

The trend of the Cottage Grove and Rough Creek fault zones appears to truncate or cut off any trend extending to the northeast from the zone of high seismicity in the Mississippi Embayment (Krinitzsky, 1972).

3. Wabash Valley Fault System

The Wabash Valley Fault System is a series of high-angle faults extending northward from the Cottage Grove and Shawneetown-Rough Creek Fault Zones through Saline, Gallatin, White, Edwards and Wabash Counties, Illinois (Heigold, 1968).

An extension has been inferred southwest into the Mississippi Valley, following the trace of Fuller's (1912) epicentral line of the 1811-1812 New Madrid earthquakes. A new 5 year study entitled "New Madrid Seismotectonic Study", is now underway (Buschbach, 1977), Hinze, et al, (1977) infer that the Wabash River Fault System (described below) is an actual extension of the New Madrid Fault. The lineation that leads to this interpretation is shown in Figure 9A where the fault map of southeastern Illinois has been expanded (Stauder, 1977).



(AFTER HEIGOLD, 1968)

FIGURE 9 FAULT MAP OF SOUTH EASTERN ILLINOIS.

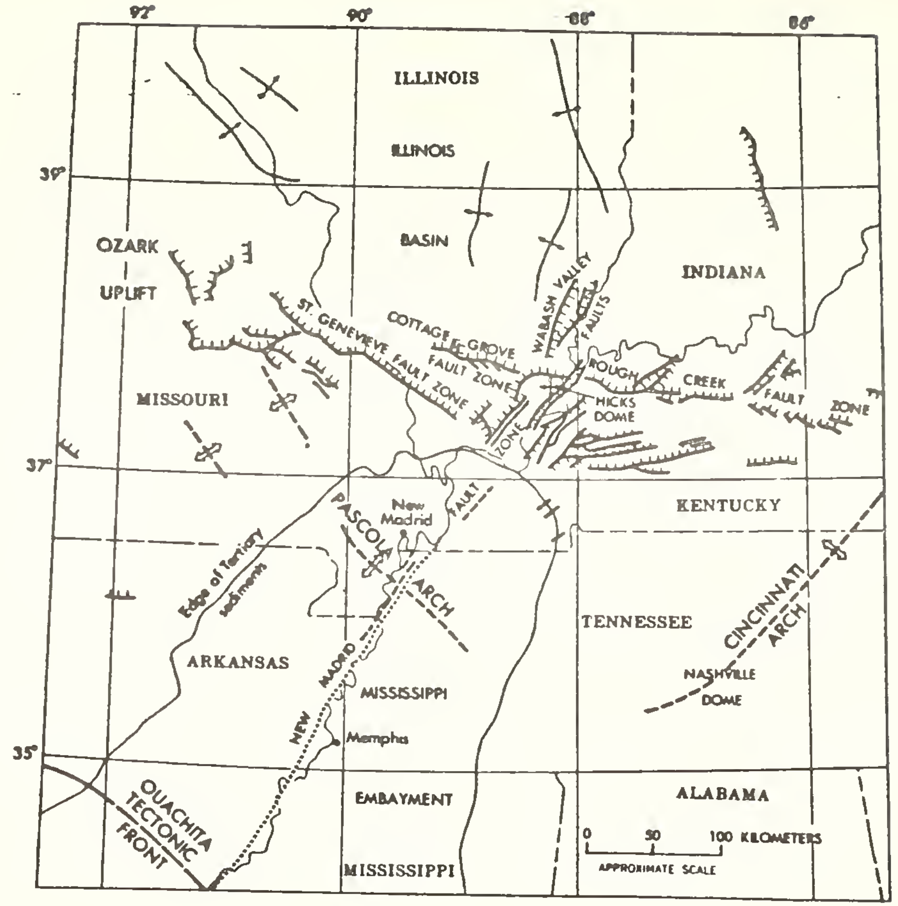


FIGURE 9A TECTONIC MAP OF THE SOUTHEAST MISSOURI SEISMIC ZONE (From Stauder, 1977, after Hadley and Devine, 1974)

Faulting in Indiana which is not considered of significance in describing the regional geologic environment is described in a later section, Indiana Geology.

EARTHQUAKE RELATIONSHIPS

General

Based on a study of the regional seismic history and geologic structure, certain relationships can be seen or hypothesized. These relationships provide a basis for estimating the location and size of future earthquakes in the region. Such estimates will be developed in later sections of the report on Probability and Design Earthquakes.

It is important to realize that not all earthquakes can be reasonably related to known structure. The resulting uncertainty must be considered in estimating future occurrences, leading to the unassigned or "floating" earthquake in design.

On Figure 10, the epicenter map (Figure 4) and tectonic map (Figure 8) are superimposed, illustrating the general regional relationship between geologic structure and earthquakes.

Seismic Regions

Nuttli (1973a) has defined seismic regions in the mid-continent for the purpose of defining "design earthquakes". His recommendations for design earthquakes are discussed in a later section. We will herein discuss the seismic regions which affect Indiana as they relate to the regional seismo-tectonic environment.

These regions are shown in Figure 11. Nuttli's regions are as follows:

1. New Madrid faulted zone (southeast Missouri, northeast Arkansas, southern Illinois, western Kentucky, western Tennessee, and northwestern Mississippi); 2a. Wabash River Valley faulted zone (southeastern Illinois and southwestern Indiana); 2c. Western Ohio seismic region (includes southeastern Michigan):

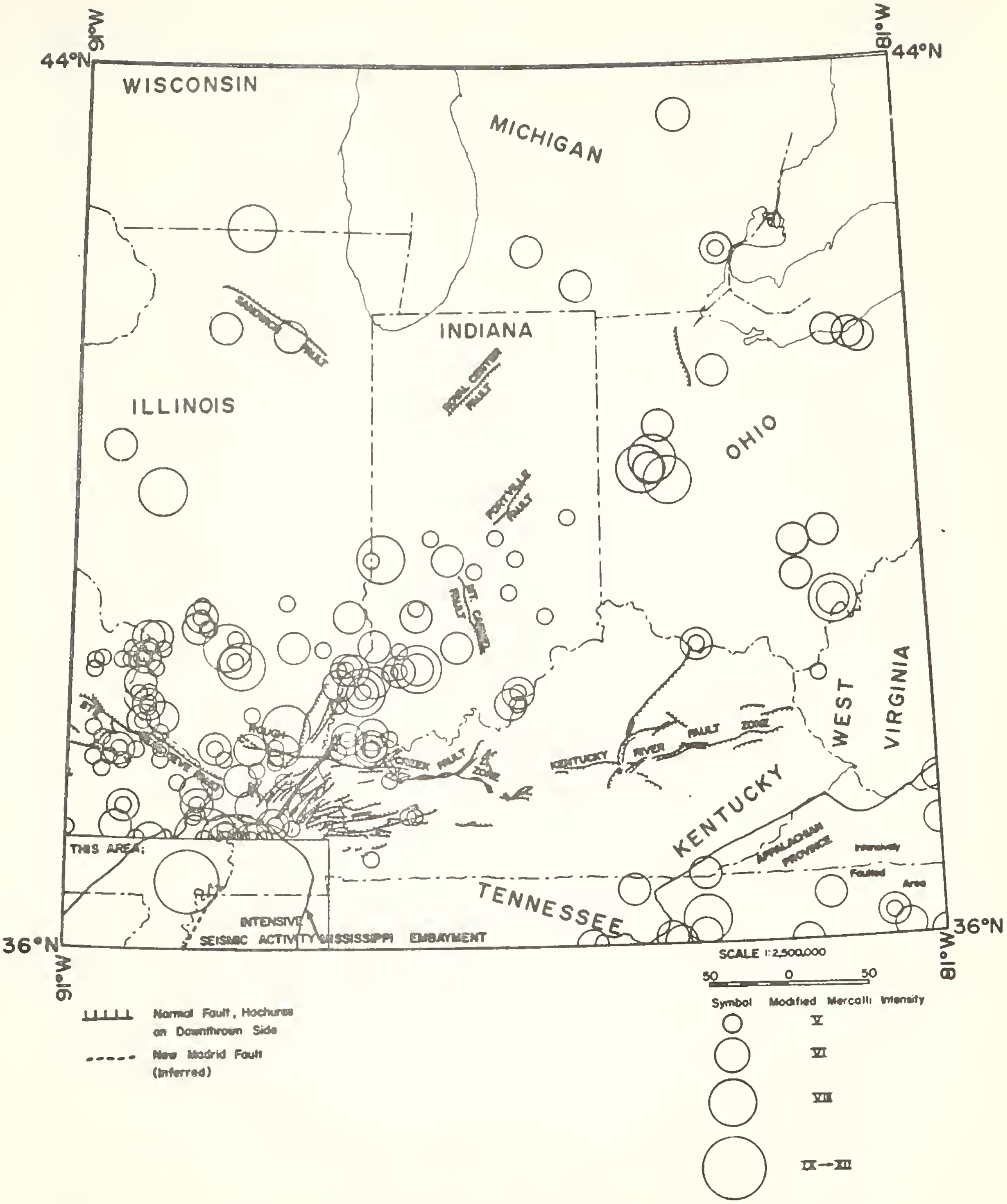
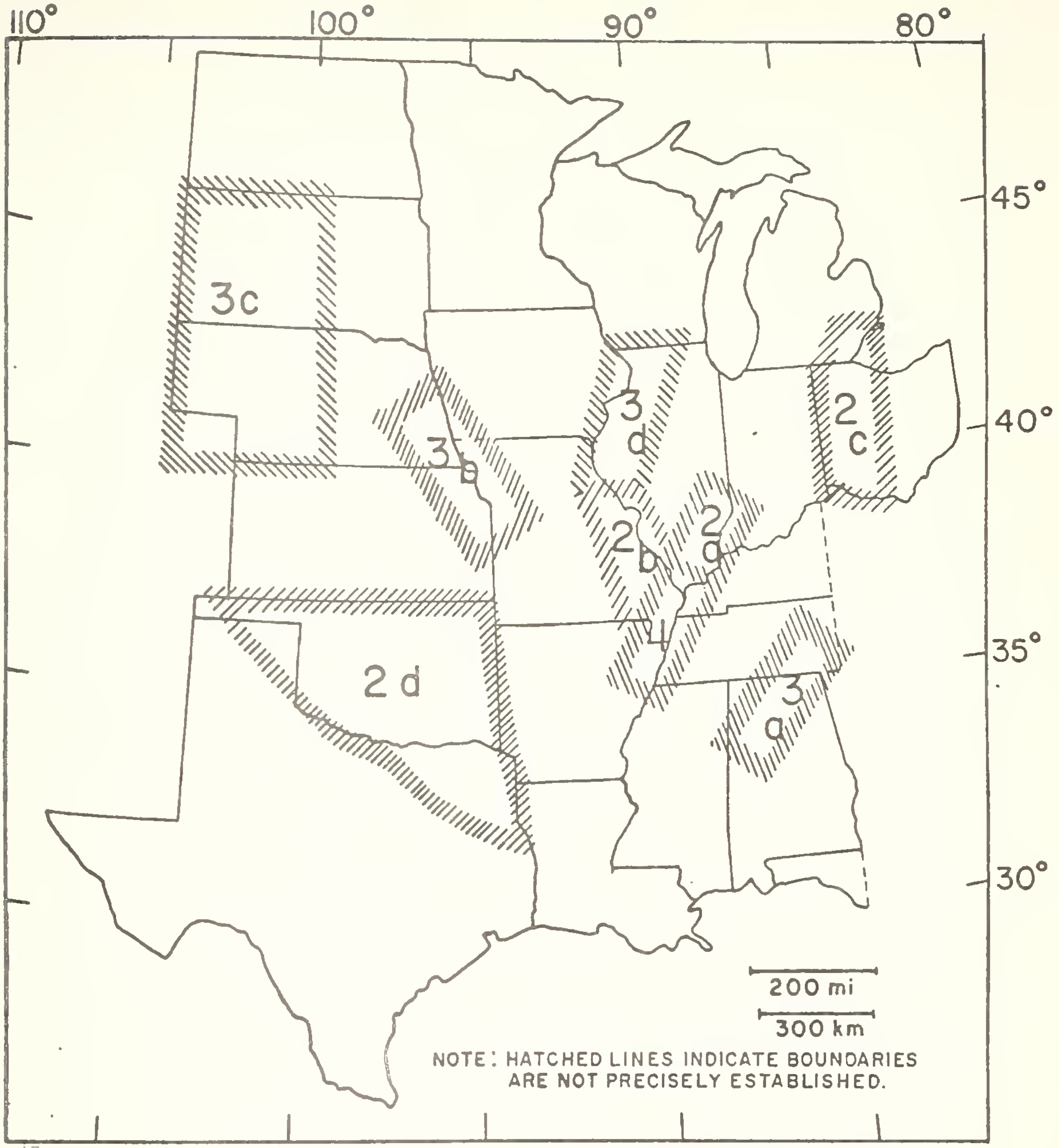


FIGURE 10 REGIONAL SEISMOTECTONIC MAP.



NOTE: HATCHED LINES INDICATE BOUNDARIES ARE NOT PRECISELY ESTABLISHED.

(AFTER NUTTLI, 1973a)

FIGURE 11 APPROXIMATE BOUNDARIES OF SEISMIC REGIONS 1, 2, AND 3 IN THE CENTRAL UNITED STATES.

Although geological names have been assigned to some of the seismic regions, it has not been established that there is a causal relation between these geologic structures and present-day earthquakes. There has been no observed surface faulting associated with earthquakes of the past 100 years in the Central United States, such as commonly is seen along the San Andreas Fault in California. As more studies of this kind are undertaken, the relationship of earthquake activity to particular faults will begin to be established.

Seismic region 2c has been assigned a geographical name rather than a geological name because there are no obvious geological structures that coincide with existing earthquake epicenters.

Fig. 11 places approximate boundaries on the seismic regions. The hatched lines are intended to indicate that the boundaries of the regions are not precisely established. These regions should not be confused with seismic risk zones, such as those delineated on Algermissen's 1969 map. Rather, seismic region 1 indicates a particular area, anywhere in which an earthquake of a certain specified size (the design earthquake for region 1) can be expected to occur. Damaging effects of an earthquake in seismic region 1 can extend far beyond the limits of the region, into areas which are considered almost aseismic. (Nuttli, 1973a).

New Madrid Seismic Zone

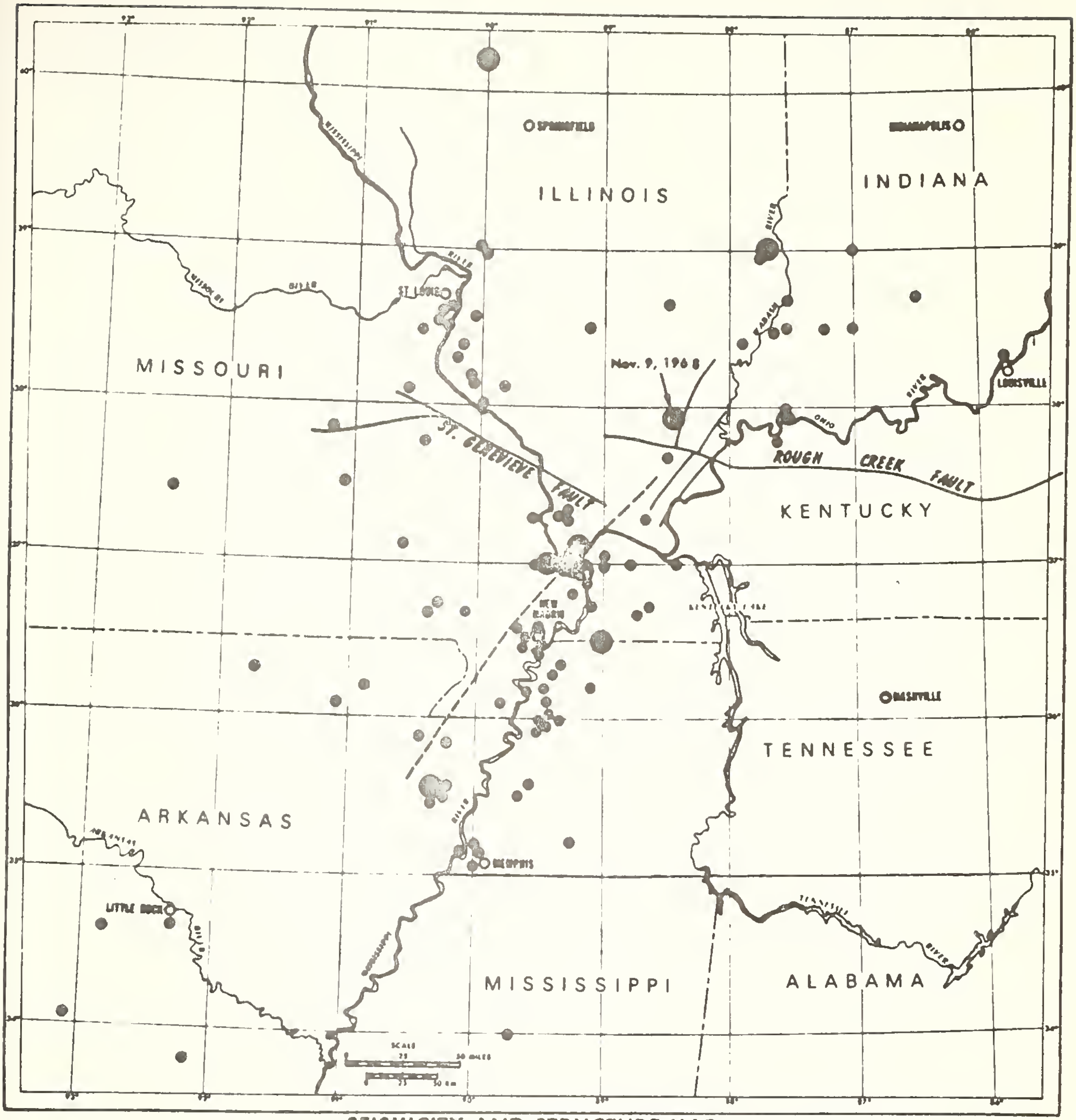
The New Madrid seismic zone, defined by Stauder and Bollinger (1963), is a zone of relatively high seismicity that extends from Memphis, Tennessee, northeasterly to the vicinity of the Illinois-Indiana border. The seismicity and principal structure of the region are illustrated in Figure 12. This figure shows apparent correlation between seismicity,

known faulting, and the trend of principal rivers. The New Madrid Seismic zone, which is approximately 75 miles wide near its center at the mouth of the Ohio, has been mapped as a high seismic risk area by Algermissen (1969), Algermissen and Perkins (1976) and by Sharpe, (1977).

All historic evidence indicates that damaging earthquakes (VII or higher) will not originate east of the New Madrid Earthquake Zone where the epicenters of all destructive and nearly all the smaller modern earthquakes have occurred, and probably will continue to occur. The reader is reminded that the record is inadequate.

The epicentral areas of all earthquakes with intensities of IX or greater coincide with the area where the northeast-trending New Madrid Faulted Belt intersects the southeast-trending axis of the Paleozoic Pascola Arch. The nearly right-angle intersection would result in abnormal stress accumulations. Partial relief of these high stress concentrations may well account for the amount of seismic activity in the New Madrid-Reelfoot Lake area. Furthermore, it may provide a logical reason to predict that future epicenters of high-intensity shocks would be confined to this portion of the New Madrid Faulted Belt. This also provides a logical reason to predict that future epicenters of damaging shocks (Intensity VII or greater) would continue to be confined to this western part of the New Madrid Faulted Belt. Also, high intensity shocks (IX or greater) have occurred only in the part of this structure that crosses the Pascola Arch (Stearns and Wilson, 1972).

In its report to the Mississippi-Arkansas-Tennessee Council on Governments (MATCOG), M & H Engineering (1973) supports Sterns and



SEISMICITY AND STRUCTURE MAP (AFTER GORDON et al,1970)

Epicenters of Intensity V or Greater Shown From 1869-1968

LEGEND

● EARTHQUAKE MAXIMUM INTENSITY V - VII

● EARTHQUAKE MAXIMUM INTENSITY VII - VIII

○ CITIES

MAJOR FAULT ZONE

FIGURE 12 SEISMICITY AND STRUCTURE MAP.

Wilson's explanation of earthquake occurrence in the Mississippi Embayment. The mechanism postulated by Stearns & Wilson rationalizes the intersection of the Pascola Arch anticline and the Mississippi Embayment syncline. As the syncline yields under the weight of embayment sediments, the bending is resisted by the arch. The restraint of the intersection creates concentrations of both bending and shear stresses. They reasoned that the preponderance of earthquake epicenters in the area of New Madrid, Missouri, were the result of block faulting resulting from the inter-reaction between the downwarping of the Mississippi Embayment and the unwarped Pascola Arch (M & H Engineering, 1973).

Sheet et al, (1974) have presented evidence based on a detailed investigation of 38 moderate sized earthquakes covering a time span of 12 years since 1962 which illustrates the local state of stress and orientation of faulting. The area under investigation centered around New Madrid, Missouri with a radius of about 150 km. Two separate faulting directions were noted. One direction parallels the New Madrid Fault Zone as shown on Figure 12 but is almost located upon the Mississippi River while the second trend is oriented northwest-southeast and crosses the first trend at and parallel to the Pascola Arch (see Figure 9A). This intersection appears to be the center of rotation of a complex state of stress where north of the intersection a compressive stress dominates (thrust faulting) while south of the intersection, tensile stress (normal faulting) dominates. However, strike-slip faulting is known to be the case which is inconsistant with the above. In order to perform adequate studies to evaluate the midwest earthquakes source mechanisms, more larger earthquakes (m_b > 5) would be required.

Regardless of when they originated, and most writers have suggested that they are very old, movement is continuing to the present along or near the New Madrid, Cottage Grove, and the St. Genevieve faults in western Kentucky, southwestern Indiana, southern Illinois, southeast Missouri, and northwesternmost essee according to Sterns & Wilson, 1972. However, Quaternary (geologic time from the present to 3 million years ago which includes the four glacial periods) displacements have not been demonstrated nor has present-day seismic activity been attributable to these faults. (Nuttli, 1976).

It is believed that the 1968 southern Illinois earthquake is related to the Wabash Valley Fault System, although the epicenter is about 10 miles west of the mapped portion of this system (Stauder and Nuttli, 1970).

Mississippi Embayment-St. Lawrence River Valley Lineation

The suggestion is frequently advanced that a straight line may be drawn between the historically seismically violent area of St. Lawrence Valley and New Madrid, Missouri areas. (see, for example, Woollard, 1958, Woollard, 1969). This line would pass through clusters of epicenters in Buffalo, N. Y. and in western Ohio. If this seismic lineation were valid, it would be logical to assume that an earthquake equal in intensity to either the New Madrid or St. Lawrence Valley shocks could occur in any place along this line. However, no real evidence exists to connect those two earthquake active areas. While there are similarities in geologic conditions between those two areas, there are no such geologic similarities in the extensive area between these two locations (Fox, 1970).

Regardless of when they originated, the most [illegible] have suggested that they are very old, [illegible] along or near the New Madrid [illegible] in western Kentucky [illegible] Missouri, and [illegible]

[illegible]

in geologic [illegible]

similarities [illegible]

Krinitzsky (1972), in his discussion of the Patoka Damsite, says that some large global pattern may encompass a structural trend from the Mississippi Embayment toward the St. Lawrence Valley. However, he gives the opinion that in the "Area of Concern" which refers to southern Indiana, there is an apparent discontinuity in the character of geological development. Also, there are apparent discontinuities in the pattern of present day seismic activity. These findings are further supported by Sbar and Sykes (1973). The earthquake activity in western Ohio which has often been pointed to in support of the lineation, is restricted to a small area and appears to reflect a localized center of activity associated with the junction of the Findlay Arch and Kankakee Arch (Krinitzsky, 1972). However, ongoing geophysical studies mentioned by Richardson et al (1977) show magnetic anomalies trending easterly across the southern half of Indiana. These anomalies may reflect buried basement features that may prove or disprove such an implied lineament.

Earthquake Triggering Mechanisms

Heigold (1968) has postulated several possible triggering mechanisms for earthquakes in the southern Illinois-Indiana area; they include 1) sudden changes in barometric pressure, 2) changes in surface water loads, 3) earth tides, 4) crustal rebound from unloading of glacial ice, and 5) crustal sinking due to recent deposition in the Mississippi Embayment region.

Sbar and Sykes (1973) feel that it is unlikely that glacial loading is the primary mechanism of earthquake generation in eastern North America, because seismic activity extends far beyond the southernmost

point covered by the Continental ice sheet. They suggest a relationship between earthquakes and highly stressed unhealed faults, somehow associated with the phenomenon of sea-floor spreading (Sbar and Sykes, 1973).

As part of a 5 year seismotectonic study of the midwest (Buschbach, 1977), Hinze et al (1977) have prepared a comprehensive overview of the midwest tectonics. They discuss three general categories of tectonic hypotheses that will be studied in order to understand the seismicity of the midwest. The categories are: resurgent tectonics, regional thermal expansion and contraction, and isostatic warping. It is hoped that these studies will answer the questions about the past sources and causes of earthquakes in the midwest as well as help to predict future seismicity.

INDIANA GEOLOGY

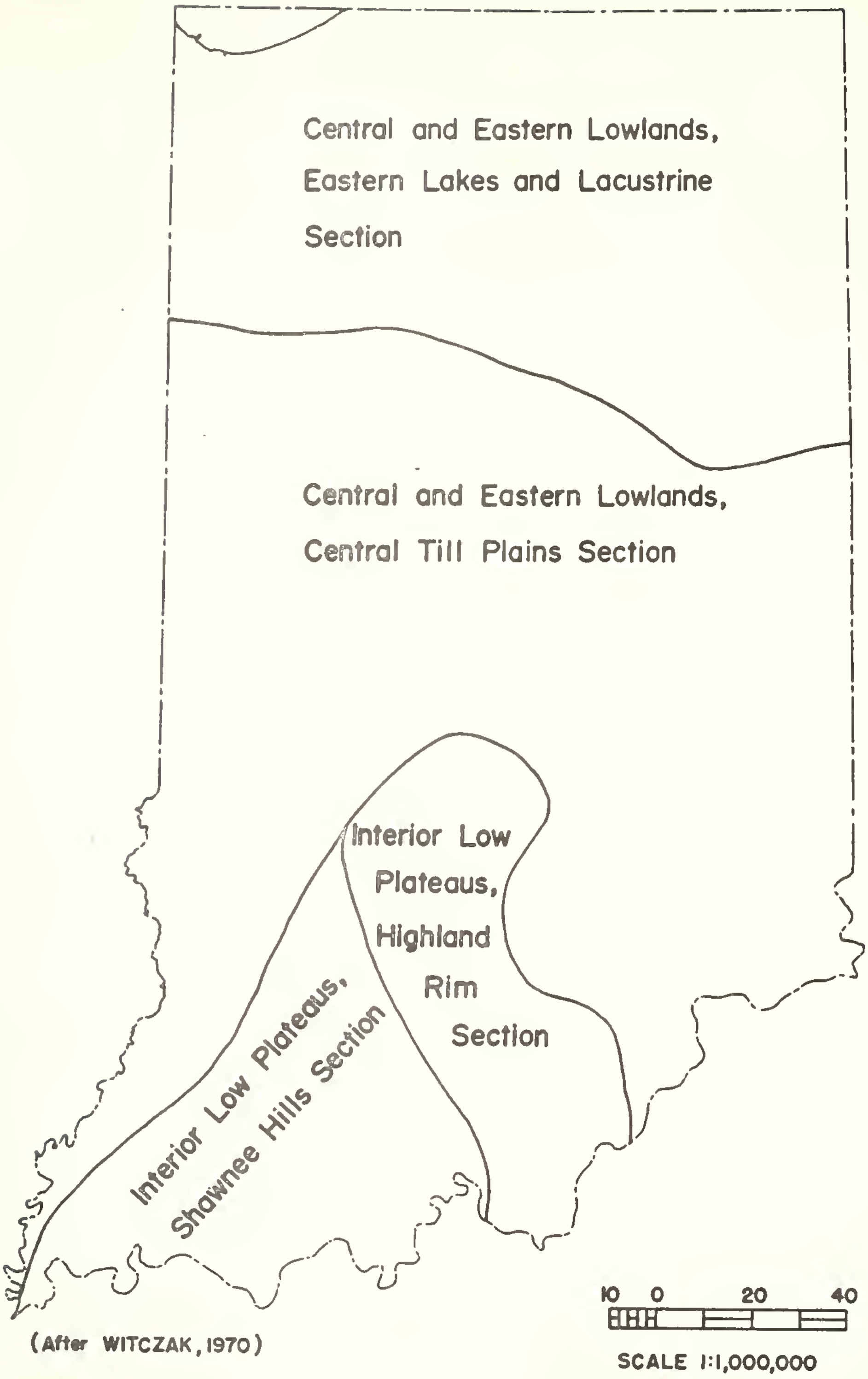
General

In this section we will review the geology of Indiana for two purposes. First, geologic conditions in the state, especially tectonics, will be related to the regional condition, so that we may assess the likelihood of earthquake occurrence in the state. Secondly, local geologic conditions are extremely important in predicting how a site and structures at a site will respond to both near and distant earthquakes.

Physiography

Most of Indiana lies within the Central and Eastern Lowlands Physiographic Province. The northern fourth of the state lies within the Eastern Lakes and Lacustrine Section of this Province (Northern Lake and Moraine Region), while the middle third lies within the Central Till Plain Section (Central Drift Plain or Tipton Till Plain). The southern part of the state, below the limit of glaciation, lies within the Blue Grass, Highland Rim, and Shawnee Hills Sections of the Interior Low Plateaus Physiographic Province. These physiographic divisions are shown on Figure 13. The central division, is a depositional plain of low relief, underlain largely by thick glacial till and modified only slightly by postglacial stream erosion.

The northern division is characterized by greater relief than the central division, being very hilly in some areas; but even in these areas, the uplands are interrupted by lowlands and plains of little relief. Landforms in this division are mostly of glacial



(After WITCZAK, 1970)

FIGURE 13 PHYSIOGRAPHY OF INDIANA.

origin. A large variety of depositional forms is present, including end moraines, outwash plains, kames, lake plains, valley trains and kettle holes, as well as many related post glacial features such as lakes, sand dunes, and peat bogs.

The roughest topography in Indiana is formed in the southern division. Landforms in this division are primarily the result of normal degredational processes, such as weathering, stream erosion, and mass movement. The middle part of the southern division was not glaciated and the topography strongly reflects the nature of the parent bedrocks. The units on either side were glaciated, but the influences of glaciation were minor and the physiography is largely bedrock controlled. An exception in part is the Wabash Lowland where many lacustrine areas, valley trains and outwash plains have developed as a result of glacial activity (Sisiliano and Lovell, 1971).

Witczak (1970) has recommended a system of classification of physiographic units in Indiana for engineering purposes. It is felt that this system is also well suited to the present study. Wticzak's recommended units for Indiana are described in Appendix B and shown on Figure 14.

GEOLOGY

Glacial:

Most of the surface of Indiana has been glaciated to varying degrees by the various continental glacial advances. The south central portion of the State was not affected by the sculpturing effects of the ice sheet, thus the topography, drainage and soils have been formed through the weathering of the Paleozoic sediments. The limits of glaciation are shown on Figure 15, based on Wayne (1958). Wayne has prepared a map of glacial drift thickness (Wayne, 1956).

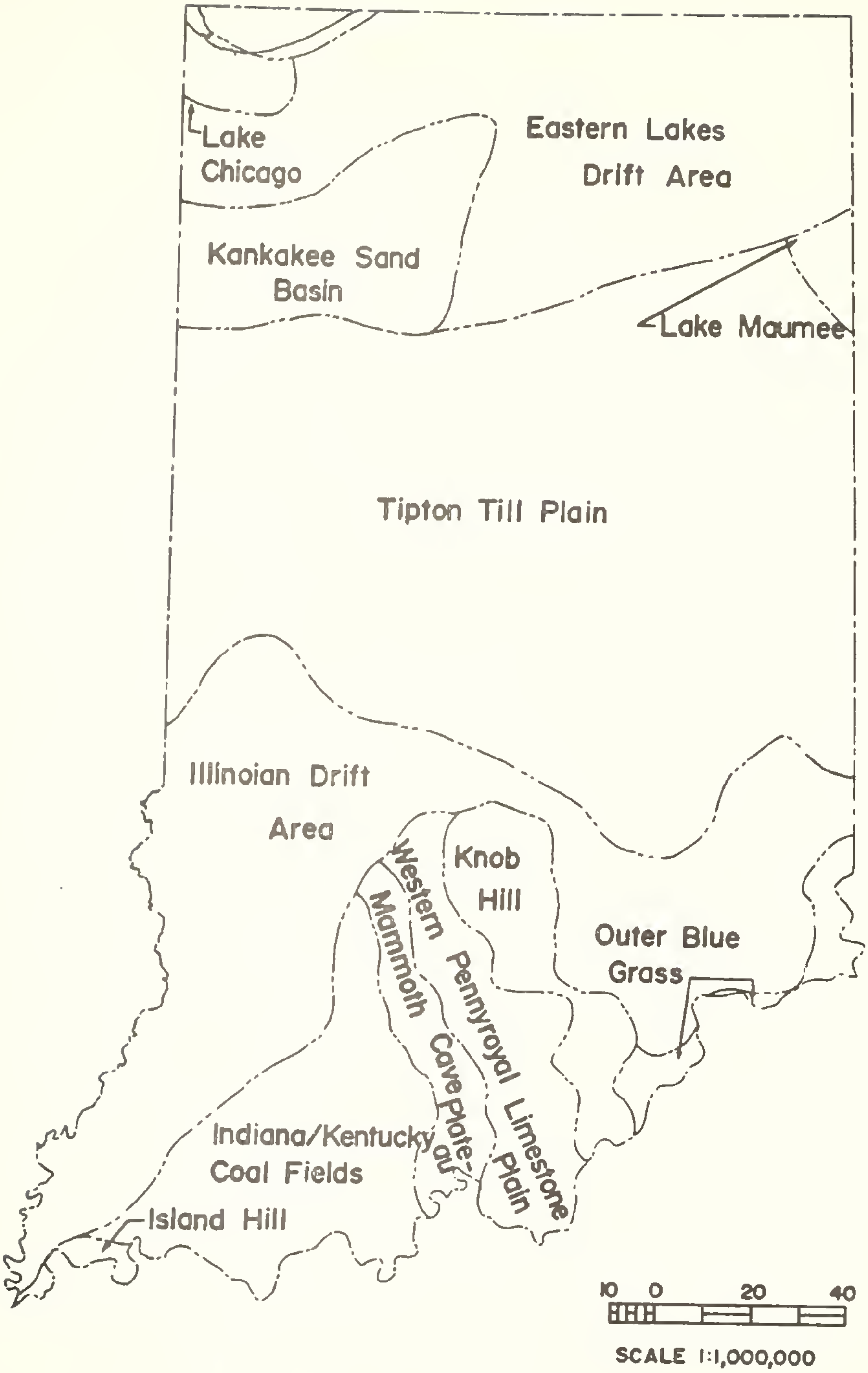
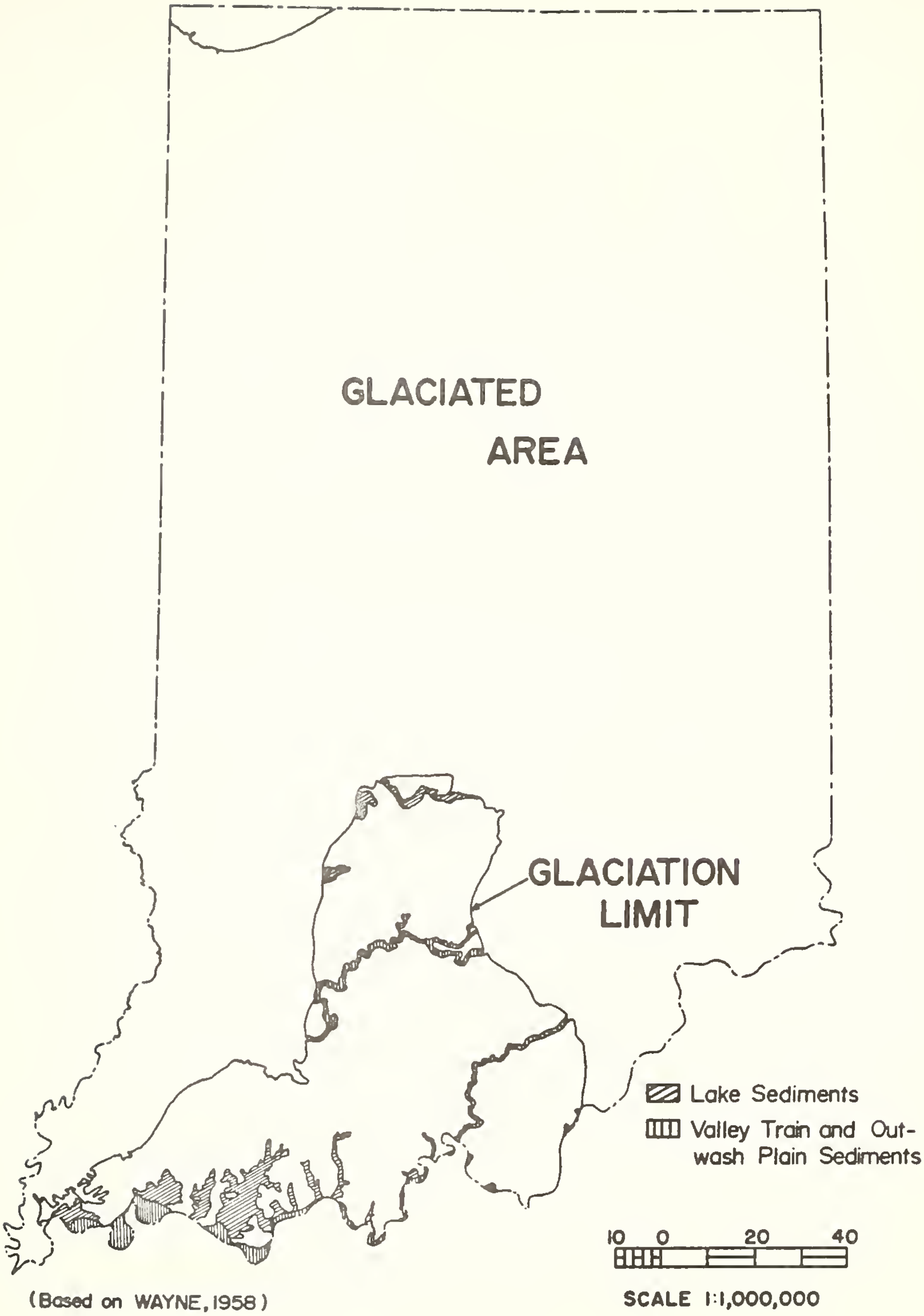


FIGURE 14 ENGINEERING PHYSIOGRAPHIC DIVISIONS.



(Based on WAYNE, 1958)

FIGURE 15 LIMIT OF GLACIATION.

Much of the bedrock topography is covered by glacial drift. The thickness of drift ranges from 50 to 100 feet in the South to more than 500 feet in the North.

The recently completed Regional Geologic Map of Indiana by the Indiana Geologic Survey, in 8 parts, each covering a $1^\circ \times 2^\circ$ quadrangle, includes surficial (glacial) geology.

Engineering Soil Studies

Engineering soils maps and reports for many counties in Indiana have been prepared under the auspices of the Purdue Joint Highway Research Project. These are recommended for studies of surface geology in local areas.

Supplementary Chart No. 1 of the Regional Geologic Map Series of the Indiana Geologic Survey, by Henry H. Gray (1973) is entitled "Properties and Uses of Geologic Materials in Indiana". This chart is an excellent summary of the engineering significance of the surficial materials found in Indiana. It is best used in conjunction with the 250,000 scale Regional Geologic Maps.

BEDROCK:

An excellent and thorough account of the bedrock geology and stratigraphy is presented in the Handbook of Indiana Geology by Cummings (1922).The 250,000 scale Regional Geologic Map includes bedrock geology in detail.

FAULTING:

The principal structural feature in Indiana is the Mt. Carmel Fault. It extends a known distance of 50 miles, trending south by southeast from southern Morgan County, across Monroe County and parts of Lawrence and Jackson Counties, and enters northwest Washington County. The fault is thought by some to have significantly greater extent, but its surface trace is lost to the north beneath glacial drift, and to the south beneath residual soil. The fault is a normal fault with vertical displacements of as much as 175 feet.

Located along the southeast flank of the Illinois Basin, the fault is one of many similar-scale structural features within the basin and along the basin margins.

Numerous subsidiary fractures are found as far as 1-1/2 miles from both sides of the fault. (Shaver and Austin, 1972 and Frey and Lane, 1966).

The Fortville Fault is interpreted as a northeast trending normal fault with its downthrown side to the southeast. The fault is mapped as being 55 miles long, extending through Madison and Marion Counties and the northwest corner of Hancock County.

The Royal Center Fault likewise is interpreted as a northeast treading normal fault with its downthrown side to the southeast. The fault extends from Kosciusco County southwest through Fulton and Cass counties, and is mapped as 48 miles long.

The Royal Center and Fortville Faults have been recognized only in recent years. The faults are mappable only from subsurface data because thick glacial deposits obscure their traces at the bedrock

surface. The faults are mapped on the surface of the Trenton limestone (Dawson, 1971).

PART II - TASK 4 - PROBABILITY AND STATISTICS

INTRODUCTION

In this Part we present the results of Task 4 (Probability and Statistics) and Task 5 (Design Earthquake).

The findings of Phase A of this study as it relates to Task 4 and Task 5 were presented to the JHRP Board Meeting on December 28, 1972. The major conclusion relating to these two tasks was that:

1. We can expect continued seismic activity from at least two sources. A smaller earthquake of probable Richter Magnitude 6 from the nearby Wabash River Fault System and a larger earthquake from the New Madrid (Missouri) Fault System with an expected surface wave magnitude of 7.

In this part, the results of Part I (Tasks 1, 2 and Task 3) are used to establish recurrence relationships for earthquakes in the Indiana area as well as possible quantitative descriptions of design earthquakes. These results will be used directly in Task 6, (Site Response) and Task 7 (Response Spectra and Time History).

EARTHQUAKE RECURRENCE PROBABILITY

General

In the December 28, 1972 report for Phase A of this study, it was recommended that:

> "Consideration--be given to the use of probability theory in assessing the factor of safety of structures based on a study of the frequency of occurrence of earthquakes in the Indiana area."

To permit the above, this section provides an estimate of the frequency of earthquake occurrence in the region, and in the Indiana area.

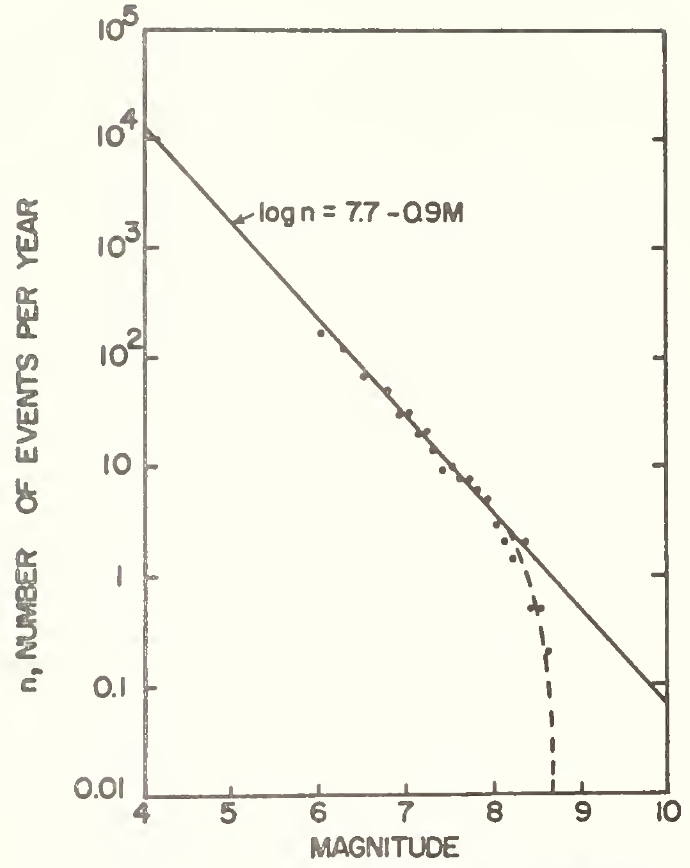
Worldwide Recurrence Relationship

The worldwide pattern of earthquake occurrence reveals that the number of events of a given size earthquake in a given period varies inversely with the size of the earthquake. In other words, there will be fewer large events than small events. Or, the average interval between large events will be greater than between small events. This frequency relationship is seen to plot almost as a straight line on a semi-logarithmetic plot as shown in Figure 16 (after Housner, 1970). The equation which defines this frequency relationship is known as the recurrence equation, and has the form:

$$\log n = a - bM$$

The "b" item defines the slope of the line and is believed to be close to constant for most regions investigated to date. The "a" term is the y-intercept defines the specific seismicity of an area, n is the number of events per year and M equals magnitude.

Of course, these statistical analyses are based on only a few hundred years of earthquake records; even less in some areas. Because earthquakes are geological events, they should be evaluated statistically over the geologic time scale. The existing record, therefore, is seen to be relatively brief. Statistical conclusions, therefore, must be viewed with caution.



(AFTER HOUSNER, 1970) *

MEAN ANNUAL FREQUENCY DISTRIBUTION OF WORLD EARTHQUAKES, 1904 - 1946.

*Robert L. Wiegel, EARTHQUAKE ENGINEERING © 1970. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

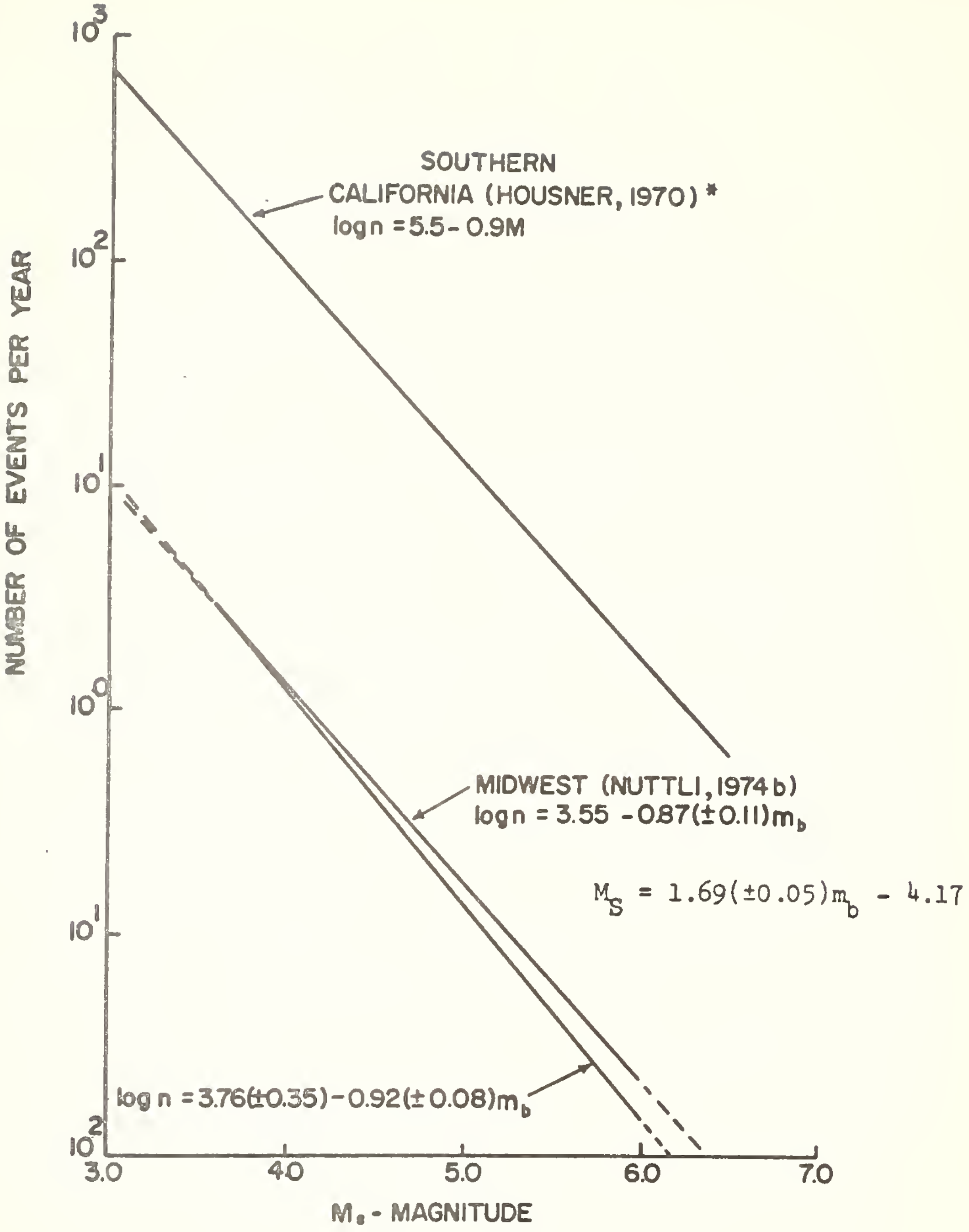
FIGURE 16 WORLDWIDE EARTHQUAKE RECURRENCE -- 1904 - 1946.

The recurrence curve is well defined for intermediate size earthquakes where the historical record is most plentiful. The curve deviates from the straight line for larger shocks where events have been relatively few and for which there is surely an upper bound. Normal records for very small shocks also are sparce because these shocks are often not felt. However, instrumental measurements of microearthquake activity have confirmed the general frequency relationship for very small earthquakes.

Regional Recurrence Relationship

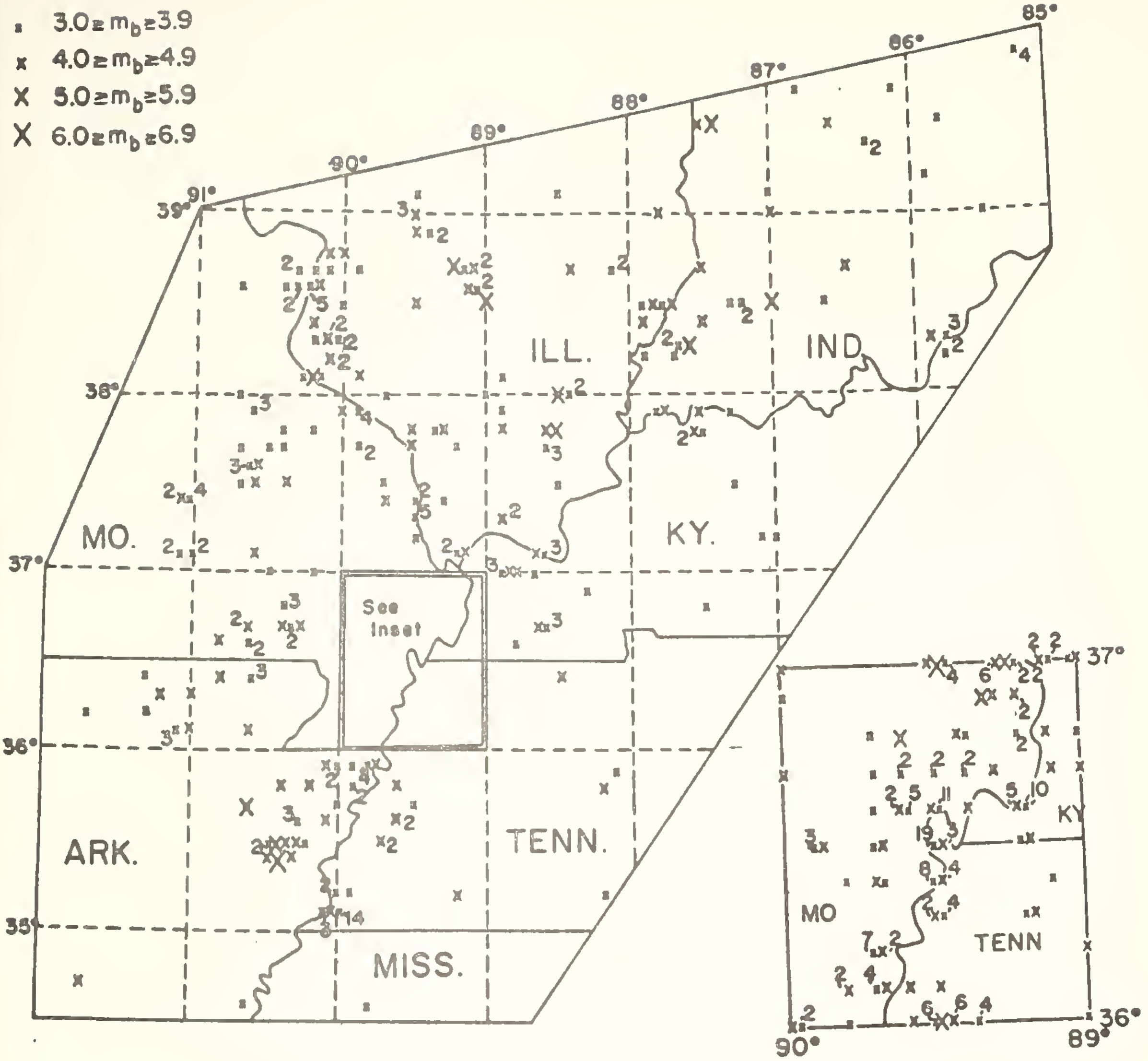
Figure 17 shows earthquake occurrence within California (Housner, 1970). Also shown is a recurrence curve for the midwest New Madrid region, suggested by Nuttli, 1974b. The body wave magnitude for the midwest data has been corrected on Figure 17 to reflect the surface wave magnitude scale according to Necioglu and Nuttli, 1974. The seismicity of the midwest can be seen to be much less intense than that of California. Earthquakes of any given size can be seen to occur about 1 percent as frequently in the midwest as in California.

Nuttli's recurrence curve for the midwest is based on the earthquake history within the region shown on Figure 18. Southern Indiana is included in this region. Nuttli notes that "the area under consideration is not one of uniform seismicity. The area could be divided into subregions which among themselves would have different recurrence relations, or different degrees of seismic risk." The Southern Indiana region clearly has a lower degree of seismicity than does the New Madrid region. However, the recurrence curve in Figure 17 is based on the average seismicity for the region of Figure 18, not the concentrated New Madrid Seismicity.



*Robert L. Wiegel, EARTHQUAKE ENGINEERING © 1970. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

FIGURE 17 REGIONAL EARTHQUAKE RECURRENCE.



MAP SHOWS AREA OF STUDY, AND THE LOCATION OF EARTHQUAKES OF $m_b \geq 3.0$ FROM 1833 THROUGH 1972. THE NUMBERS REFER TO THE NUMBER OF EARTHQUAKES WITH THE SAME EPICENTER.

FIGURE 18 REGION STUDIED BY NUTTLI, 1974.

Southern Indiana Subregion

For this study, the southern Indiana subregion was examined in two ways. The first method was by plotting the seismic history for the portion of the Nuttli region north of Latitude 37° N and east of Longitude 88° W using the earthquake data presented by Nuttli, 1974b. The results are shown in Figure 19, Curve A, by the open triangles and are compared to the midwest regional recurrence curve from Figure 17, Curve C. Curve C in Figure 19 is based on the midwest regional curve in Figure 17 but has now been corrected from body wave magnitude (m_b) to surface wave Magnitude, M_S, by the relationship (Hays, et al, 1975):

$$m_b = 0.56\ M_S + 2.9$$

In this way all the graphs on Figure 19 may be compared. For reference, Curve E, for Southern California from Figure 17 is also shown. It must be remembered, however, that these recurrence curves and subsequent statistical estimates of frequency of earthquake occurrence are highly dependent on the region chosen.

The Indiana subregion was also examined by using the return period work of Blakely and Varma, 1974. They have presented data on return periods, in decades, for Indiana by using a method to determine seismicity based on the statistics of extremes. Their results are shown on Figure 20 for Modified Mercalli Intensities IV, VI, and VIII. The numbers associated with the contours are the return periods, in decades, for a given intensity earthquake. Using the data given in Figure 20, it is possible to calculate return rates for any location within the State of Indiana. As an example calculation, we have examined the City of Evansville. Evansville was chosen because of its relatively high population as well as its proximity to sources of seismicity.

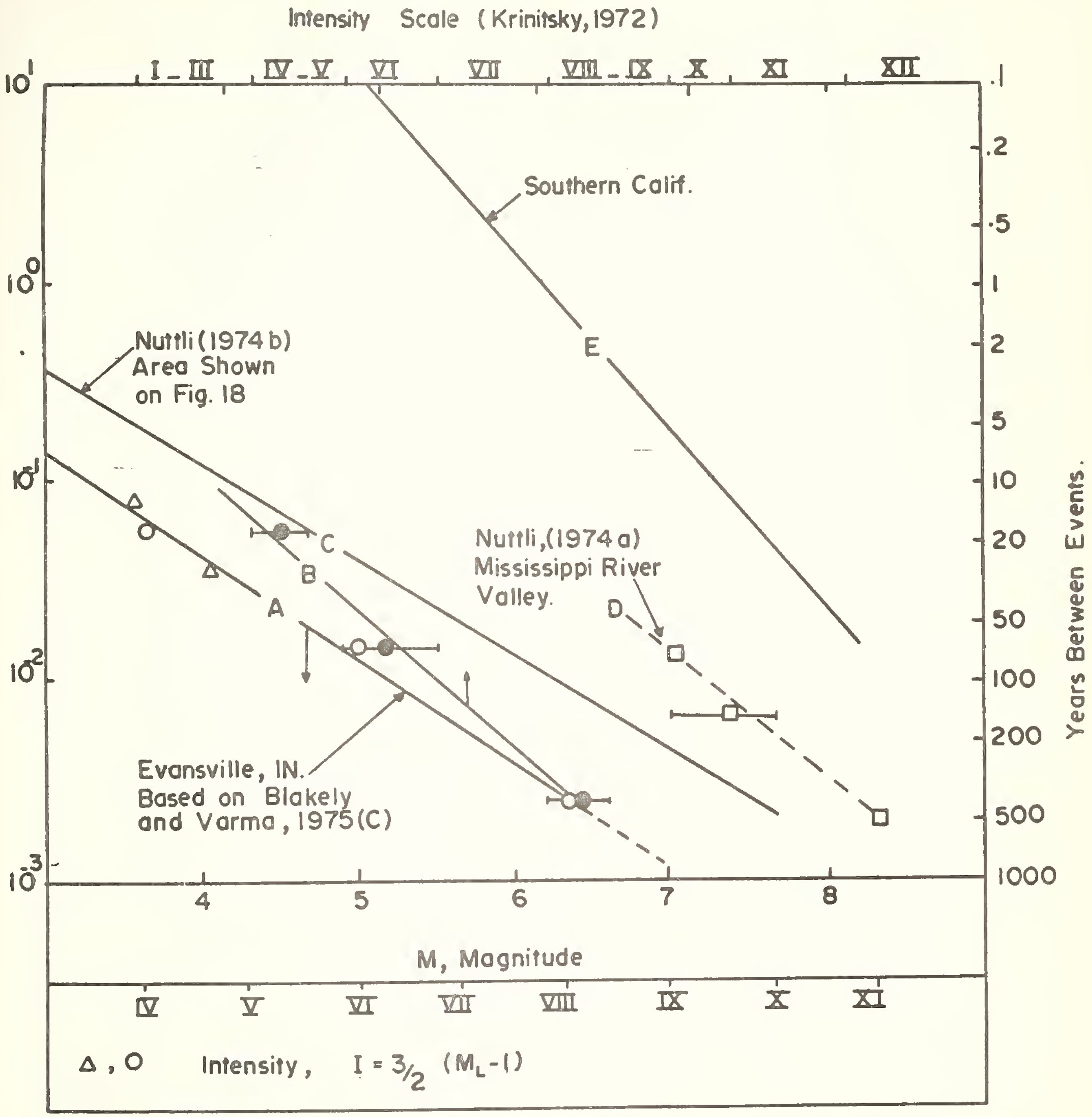
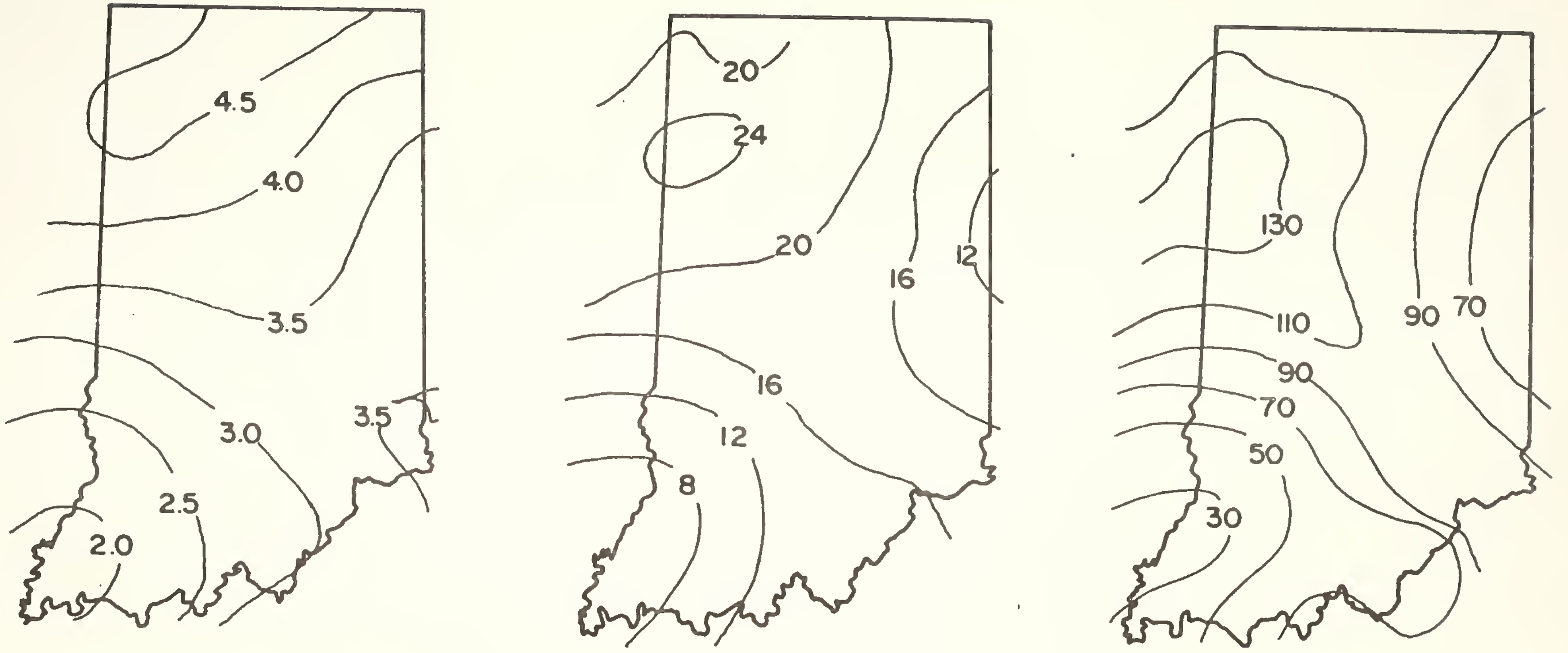


FIGURE 19. RECURRENCE INTERVAL VS. MAGNITUDE AND INTENSITY.



I = IV. I = VI. I = VIII.

After Blakely and Varma, 1974

FIGURE 20. CONTOURS OF RETURN PERIODS, IN DECADES, FOR MM INTENSITY IV, VI AND VIII.

For a given geographic location, the return periods are interpolated or extrapolated from Figure 20 and for the City of Evansville, the data points are plotted as open circles by Curve A on Figure 19. Data drawn from Figure 20 are expressed in relation to intensity rather than magnitude. We have plotted the return periods from Figure 20 using the magnitude-intensity relation shown at the bottom of Figure 19. Another magnitude-intensity relation is the intensity scale shown at the top of Figure 19, used by the U. S. Army Corps of Engineers (Krinitzsky, 1972). Using this latter intensity scale (Curve B) alters the lower magnitude relationships only.

Similar curves could be drawn for other locations within the State of Indiana and these recurrence curves would be located to the lower left of Curve A or have lower probability of occurrence.

Based on the data given in Curve A, Figure 19, obtained by two methods, for the City of Evansville, (Southwest Indiana) Table 4 has been prepared for design purposes.

TABLE 4

Recurrence Interval and Earthquake Size
for Southwest Indiana

Magnitude	Intensity*	No. Events/Yr.	Yrs. Between Events
3	III	.13	7.7
4	IV-V	.04	24.4
5	VI	.013	77
6	VII-VIII	.0037	270
7	IX	(.0011)	(900)

*Using Curve A and Intensity Scale at bottom of Figure 19.

Numbers in parenthesis are extrapolations.

Mississippi River Valley Subregion

Nuttli's recurrence Curve (C) is based on the seismic history since 1834. It thus is not "weighted" by the 1811-1812 series of major earthquakes with their many aftershocks. The recurrence curves for the area shown in Figure 18 when taking into account the New Madrid, Missouri earthquakes prior to 1833 is given by Curve D (Nuttli, 1974a). Curve D shows a significant increase in earthquake potential damage for return periods of 100 to 500 years.

Using these curves to extrapolate for future events, a shock of body wave magnitude 7.2 (comparable to the largest of the New Madrid shocks) would be expected about once every 200 to 500 years in the region. Although Curve A does not show this to be true, it is logical to assume that an earthquake originating in the New Madrid areas will be felt in Evansville. The actual response is discussed in the next section.

Nuttli states that the principal use of statistical recurrence curves is to classify and compare different regions according to their degree of activity. He cautions that in design of structures whose failure would result in great loss of life or disruption of essential services, it is necessary to consider that the largest possible earthquake for the region could occur during the lifetime of the structure. This concept will be discussed in later sections.

As discussed for the worldwide seismic recurrence relationship, the period of record is too brief to develop a strong statistical relationship. Design decisions based on these recurrence relationships should consider this uncertainty.

Possible Future Studies

The foregoing discussion provides an estimate of the frequency of recurrence of earthquakes within the midwest region (and by extension, in southern Indiana). It is possible to extend this work to develop an estimate of the frequency of recurrence of a given level of ground motion at a given site, using probability methods. This has been done by several investigators for different regions (for example Algermissen and Perkins, 1972; Cornell and Merz, 1974; Algermissen and Perkins, 1976). Similar methods should be adaptable to the Indiana area, but are beyond the scope of the present study.

TASK 5 - DESIGN EARTHQUAKES

General

Based on our study of regional earthquake occurrence and geologic relationships, it is possible to define "design earthquakes" for Indiana. The factors to be considered in developing these design earthquakes are:

1) Maximum historical earthquakes which have occurred or been felt in Indiana;
2) The maximum credible future earthquakes in the region and where these earthquakes are likely to occur, based on a reasonable extrapolation of earthquake history, consistent with our knowledge of geologic relationships (see for example Hinze et al, 1977);
3) The estimated return period for these earthquakes based on the regional statistical and probability studies.

In this section, the selection of design earthquakes for Indiana will consider future earthquakes with respect to their size, epicentral location, and probability of occurrence, as they would affect Indiana. The earthquakes will be defined in terms of their magnitudes; epicentral or maximum intensities; and intensities throughout Indiana. The earthquake motion in Indiana, for design purposes, will be defined in terms of maximum ground particle velocity and duration of shaking.

In Part III of the report, the design earthquake motion will also be represented in the form of structural response spectra. Modifications to the expected earthquake ground motion as a result of local geologic conditions also will be discussed.

In later parts of the report, the concept of risk analysis will be applied to building and highway construction. This will assist in selecting appropriate levels of earthquake motion considering the importance of the structure with regard to public safety, replacement cost, etc.

The frequency of earthquake occurrence is important in assessing the relative hazard between two areas. For example, the New Madrid area and much of California are both considered to be zones of possible major earthquake damage. However, damaging earthquakes would be expected with much greater frequency in California than in the New Madrid area. Krinitzsky (1972) cautions that estimates of recurrence are unreliable. Therefore, he says that for any structure, the failure of which might involve loss of life, one should recognize that the greatest potential earthquake may occur during the life of the structure. As will be discussed later in this report, the probability of this occurrence becomes the basis for the risk analysis approach to design. Thus the challenge is to consider the design situation where the probability of the earthquake occurrence is small, but the consequences of failure are great.

Regional Design Earthquakes

Several investigators have recently attempted to define the earthquake hazard in the midwest. They have defined "seismic zones" within which a given size earthquake might be expected to occur as a maximum credible event.

Hadley and Devine (1974) have defined seismotectonic provinces on the basis of maximum earthquake size, frequency of occurrence of

earthquakes of any size, and related geologic features. The portion of their map which relates to Indiana is presented in Figure 21A with descriptive information given in Figure 21B.

An examination of this map indicates that there are four critical earthquake conditions which would contribute to design earthquakes for Indiana. These are:

1) the New Madrid Seismic Zone (Level A-5)
2) the Wabash Valley Fault Zone (Level A-3).
3) the Western Ohio Seismic Zone (Level B-4).
4) the area east of the Wabash Valley Fault Zone (Level C-2).

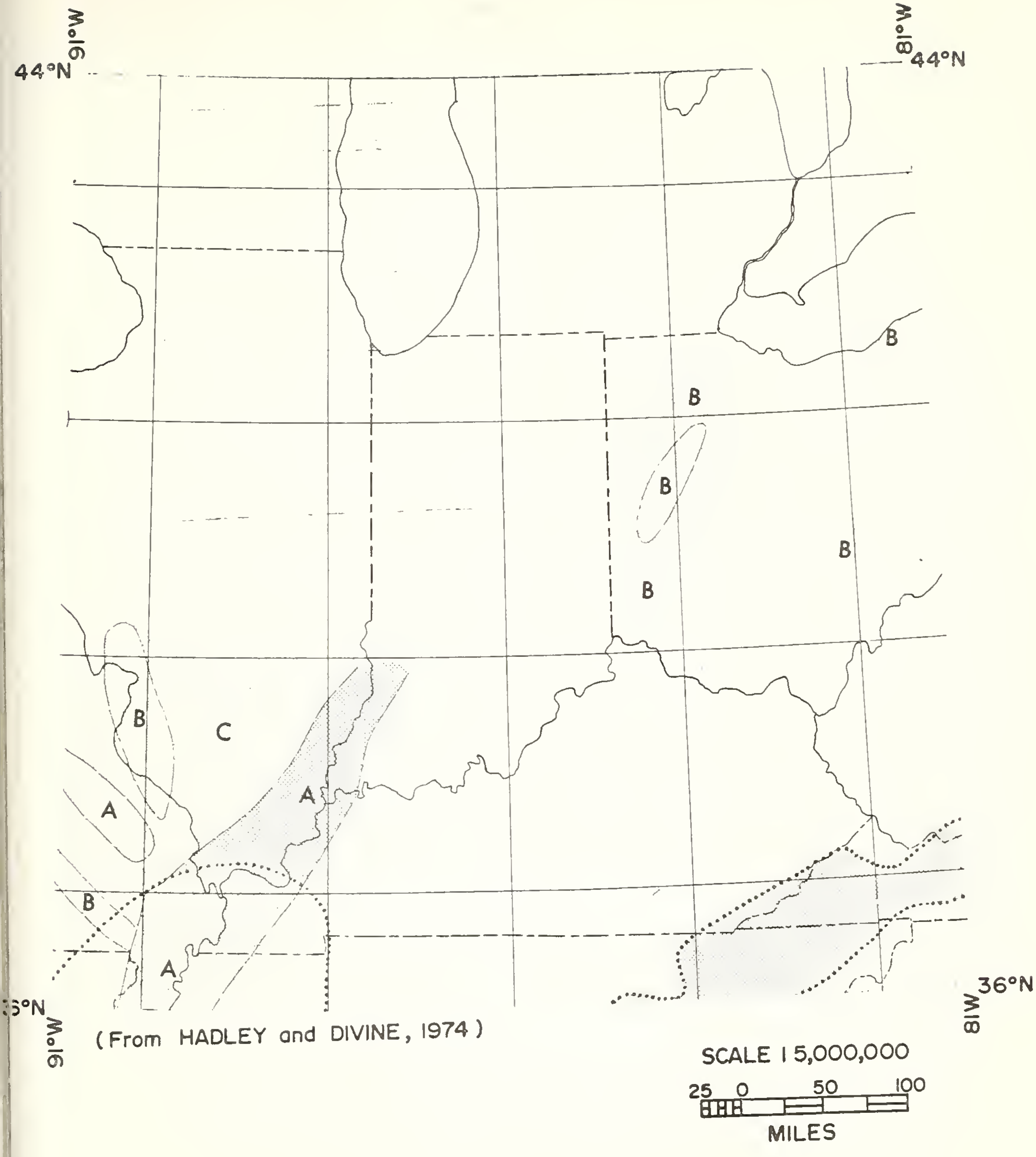
The Levels correspond to Hadley and Devine's categories of seismic activity and geologic control as described in Figure 21B. These findings are consistent with our earlier findings reported in our report for Phase A of this study.

Nuttli (1973a) has defined seismic regions as discussed earlier in this report. These regions were shown in Figure 11.

For Region 1 (New Madrid faulted zone) he recommends a design earthquake with a magnitude based on the three largest shocks of the 1811-1812 series (body wave magnitude 7.2).

For Region 2 (Wabash River Valley faulted zone, western Ohio seismic region) a design earthquake is taken as one whose magnitude is one unit less than that of Region 1 (body wave magnitude 6.2).

For Region 3 a design earthquake is taken as one whose magnitude is 1-1/2 units less than that of the design earthquake for Region 1 (body wave magnitude 5.7).



(From HADLEY and DIVINE, 1974)

FIGURE 21A SEISMOTECTONIC MAP.

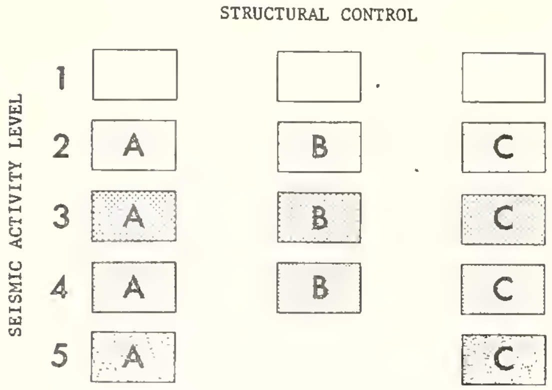
EXPLANATION

••••••••••••••••

Tectonic province boundary
Dashed where concealed by younger deposits

— — —

Very approximate limits of seismic activity areas
and (or) structurally controlled areas



SEISMIC ACTIVITY LEVEL

Level 1

Seismic frequency in epicenters is less than 8 per $10^4 km^2$. Includes large areas in which seismic frequency is 0. All areas of this level are indicated without pattern, because information about historical seismicity is insufficient to make structural analysis possible

Level 2

Seismic frequency is generally more than 8 but less than 32, and no earthquake in the area has a maximum epicentral intensity greater than MM VI. Used locally for areas of seismic frequency higher than 32 around and between areas whose epicentral pattern indicates structural control

Level 3

Applies generally to areas where seismic frequency is more than 8 but less than 32 and at least one earthquake of epicentral intensity VII or VIII is recorded. Commonly restricted to areas where epicentral distribution or relation to known structure indicates a limiting structural factor. Applies also to some areas where seismic frequency is 32 or more if no epicenters of intensity greater than VI are recorded, notably in central Virginia and the Adirondack-St. Lawrence area

Level 4

Seismic frequency is 32 or more and earthquakes of intensity VII or VIII have been recorded. Locally extended along fault trends into areas of somewhat lower seismic frequency

Level 5

Areas where one or more epicenters of intensity IX or higher are present and seismic frequency is more than 32. Where seismic frequency drops below 32 along structural trends, level 3 applies because both maximum intensity and seismic frequency decrease. No areas exist where the seismic frequency is less than 32 and earthquakes of intensity greater than VIII have been recorded

STRUCTURAL CONTROL

A

Areas in which known faults are associated with epicentral alinements or distribution, in such a way as to indicate that movements on the known faults or closely related faults have been the source of recorded earthquakes

B

Areas in which major faults are not known, but epicentral concentration and alinement indicate that movements on unrecognized or concealed faults have been the source of recorded earthquakes

C

Areas in which major faults are known, but the epicentral distribution does not indicate that they are the source of recorded earthquakes. Also, areas in which major faults or other seismically active structures are not known or indicated

FIGURE 21B SEISMOTECTONIC MAP — EXPLANATION.

Parts of the midwest outside of Regions 1, 2 and 3a, b, c and d, are included in Region 3e. These areas would be expected to experience earthquakes as large as those of Regions 3a, b, c, and, d, but with a very low probability of occurrence.

Design Earthquakes for Indiana

Based on the foregoing, the following earthquake events are important in selecting the maximum credible design earthquake levels in Indiana:

TABLE 5

Maximum Credible Earthquakes

Source	Body Wave Magnitude	Epicentral Intensity
1) New Madrid Seismic Zone	7.2	XI
2) Wabash River Valley Fault Zone	6.2	VIII
3) Western Ohio Seismic Region	6.2	VIII
4) Anywhere in Indiana	5.7	VII

This is essentially as reported in our December 28, 1972 report.

The effect of those occurrences (except Source No. 4) would vary throughout the state, since earthquake-induced ground motion attentuates with distance. In addition, these occurrences would vary, perhaps locally, due to different soil and geological conditions. Sources 1 and 2 would most strongly affect the southwest corner of Indiana. Source 3 would most strongly affect the east central part of the state.

Parts of the mid-east portion of Figures 1, 2 and 3, [illegible] and [illegible] are included in Region 3a. These areas [illegible] expected to experience earthquakes as large as those of [illegible] [illegible] of such a very low probability of occurrence.

Design Earthquakes

Based on the [illegible], [illegible] important [illegible] included:

[illegible]

Design Earthquake Parameters

Krinitzsky (1972) presents design parameters for the Patoka Damsite, 13 miles northeast of Jasper, Indiana. The design parameters given are for bedrock at the damsite and do not take into account the effect of amplification of the rock motion through overlying soil deposit(s).

For the source 1 area (Table 5) to the damsite, the epicentral distance is approximately 130 miles and with attenuation over this distance results in the recurrent peak ground motions for 0.3 to 3.0 Hz (cycle per second) waves given in Table 6:

TABLE 6

Recurrent Peak Ground Motions
for Patoka Dam
from New Madrid Seismic Zone

Acceleration	0.022 to 0.050 g
Velocity	1 to 17 cm/sec
Displacement	0.05 to 7.5 cm
Duration	160 seconds

The corresponding design parameters for source area 2 (Table 5) are given in Table 7:

TABLE 7

Recurrent Peak Ground Motions
for Patoka Dam
from Wabash River Valley Fault Zone

Acceleration	0.11 g to .44 g
Velocity	54 cm/sec
Displacement	26 cm
Duration	68 seconds

An acceleration of 0.11 g was originally given by Nuttli (1973) but increased by Krinitzsky (1972, with prior knowledge of report)

to o.44 because he felt the value of 0.11g was so low in comparison to West Coast practice. However, Nuttli (1973b) has demonstrated that the accelerations for a given Modified Mercalli Intensity are much lower in the eastern U. S. than in California. This reduction is caused by a lower frequency of the wave motion. However, designing for these lower accelerations may be unconservative because while the accelerations may be lower for a given Modified Mercalli Intensity, the correlation between ground velocity for both California and Midwest U. S. earthquakes and Intensity are the same. This aspect is unresolved and is currently under investigation. Therefore, the lower acceleration appears more realistic.

Figures 22A and B show maps of effective peak acceleration, A_a, (EPA) and Effective Peak Velocity-related acceleration, A_v, respectively, for part of the United States (ATC, 1976; Sharpe, 1977). A_a is proportional to spectral ordinates for periods of vibration in the range of 0.1 to 0.5 seconds (2 to 10 cycles per second) while A_v is proportional to spectral ordinates of a period of about 1 second (1 cycle per second frequency). These recommended peak accelerations are values "on firm ground". Further discussion of the effective peak acceleration map and effective peak velocity related acceleration map are given by Donovan et al (1976). The Patoka Damsite is located between contours 1 and 2 with EPA's of 0.05g to 0.10g, respectively. "The recommended effective peak accelerations have a probability of roughly 75 to 90 percent of not being exceeded during a 50 year period; stronger ground motion is possible. The design forces corresponding to the recommended effective peak accelerations, plus adherence to the design provisions to improve the building stability even if it yields and is damaged, will lead to

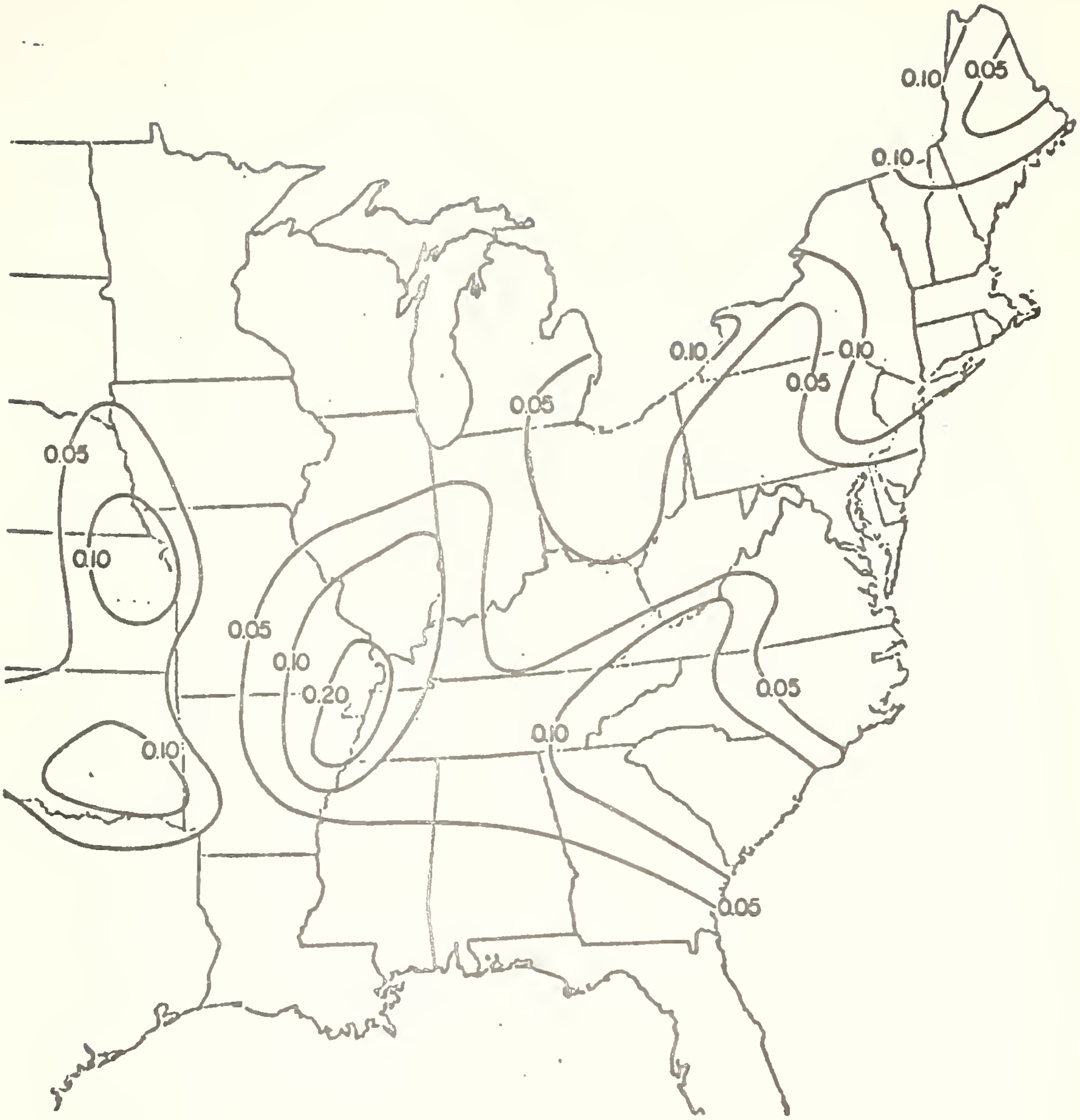


FIGURE 22A EFFECTIVE PEAK ACCELERATION IN % GRAVITY ON FIRM GROUND FOR PERIODS IN THE RANGE OF 0.1 TO 0.5 SECONDS. (SHARPE, 1977)

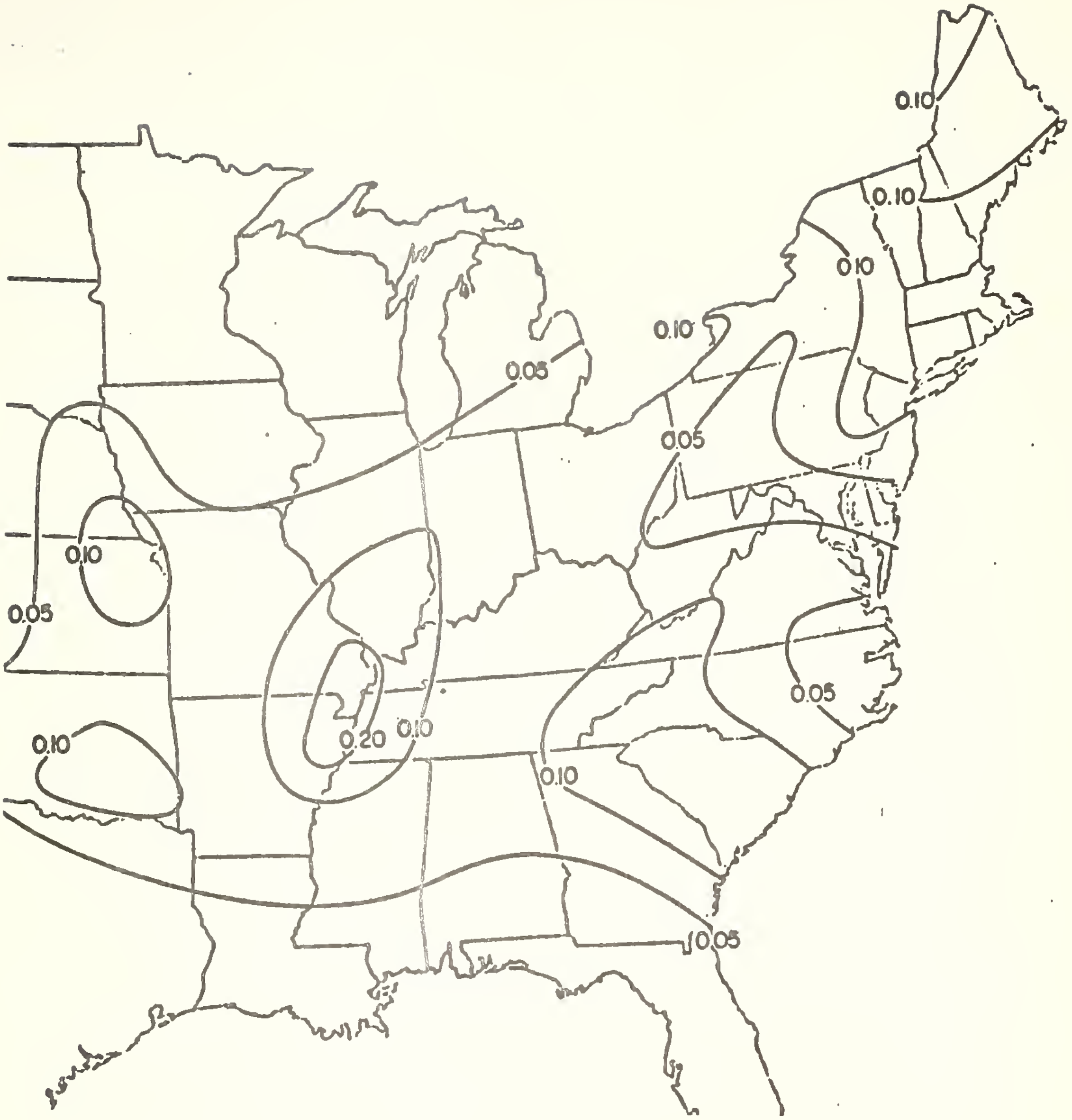


FIGURE 22B EFFECTIVE PEAK VELOCITY-RELATED ACCELERATION, IN % OF GRAVITY FOR PERIODS IN THE RANGE OF ABOUT 1 SECOND ON FIRM GROUND. (SHARPE, 1977)

structures with a reasonably high probability of protecting life safety during even stronger earthquakes." (ATC, 1976)

The results presented in Figure 22A agree with the design parameters with Sources 1 and 2 (Table 6 and 7). Though the accelerations are low, the (ground) particle velocities are not low and exceed the threshold of damage, considered to be 2 inches per second (5 cm/sec) (Nicholls, et al, 1971).

Finally, design parameters for a Source 4 earthquake, (Table 5) assuming a 20 mile attenuation, is given in Table 8

TABLE 8

Recurrent Peak Ground Motions
for Patoka Dam
from A Floating Earthquake Source

Acceleration	0.0087g
Velocity	4.3 cm/sec
Displacement	2.0 cm
Duration	40 seconds

It must be emphatically stated that the response values given in Tables 6, 7, and 8 are given for "hard rock" conditions and the actual ground response may be several times that of the bed rock input motion.

Another version of an updated "seismic risk map" is given by Algermissen and Perkins (1976) and is presented in Figure 23 for the midwest area. The map should properly be called a probabilistic hazard map as the contours represent the maximum acceleration in rock to be expected with a 90 percent probability of not being exceeded in 50 years. Also, the map is considered preliminary and will be updated in the years to come as more information becomes available. Algermissen and Perkins

(1976) clearly state "that site materials other than rock as defined here (material having a shear wave velocity of between 0.75 and 0.90 km/sec or higher), will result in accelerations that may have maximum values two to three times larger than the values shown on (their) map. In a few cases, site materials may result in accelerations slightly lower than shown on (their) map."

Unlike the seismic risk map in the 1973 Uniform Building Code the new map presented in Figure 23, allows interpolation of acceleration between contour lines. For example, according to Figure 23, the underlying bed rock of the City of Evansville, Indiana could have a peak horizontal acceleration of about 8 percent (.08g) with a 90 percent probability of not being exceeded in 50 years. This value is of the same order of magnitude as the effective peak acceleration obtained for Evansville from Figure 22A and B.

Recently, Nuttli (1974a) has presented estimated ground velocity and duration time of longer period surface wave motion for a major earthquake (Source 1, Table 5) occurring in Southeast Missouri. This information is presented in Figure 24. These values of estimated ground velocity on hard rock and duration are somewhat lower than those given by Krinitzsky, 1972. However, if one moves the epicenter of the hypothetical major southeast Missouri earthquake, upward, northeasterly, along the inferred New Madrid fault zone toward the Wabash River Fault system, this possibility approaches the Source 2 design earthquake (Table 7). Based on the area shown as Region 1 of Figure 11, the epicenter has been moved northeasterly along the New Madrid Fault zone to Cairo, Illinois. With this revised epicenter, a second set of contours has been drawn on Figure 24

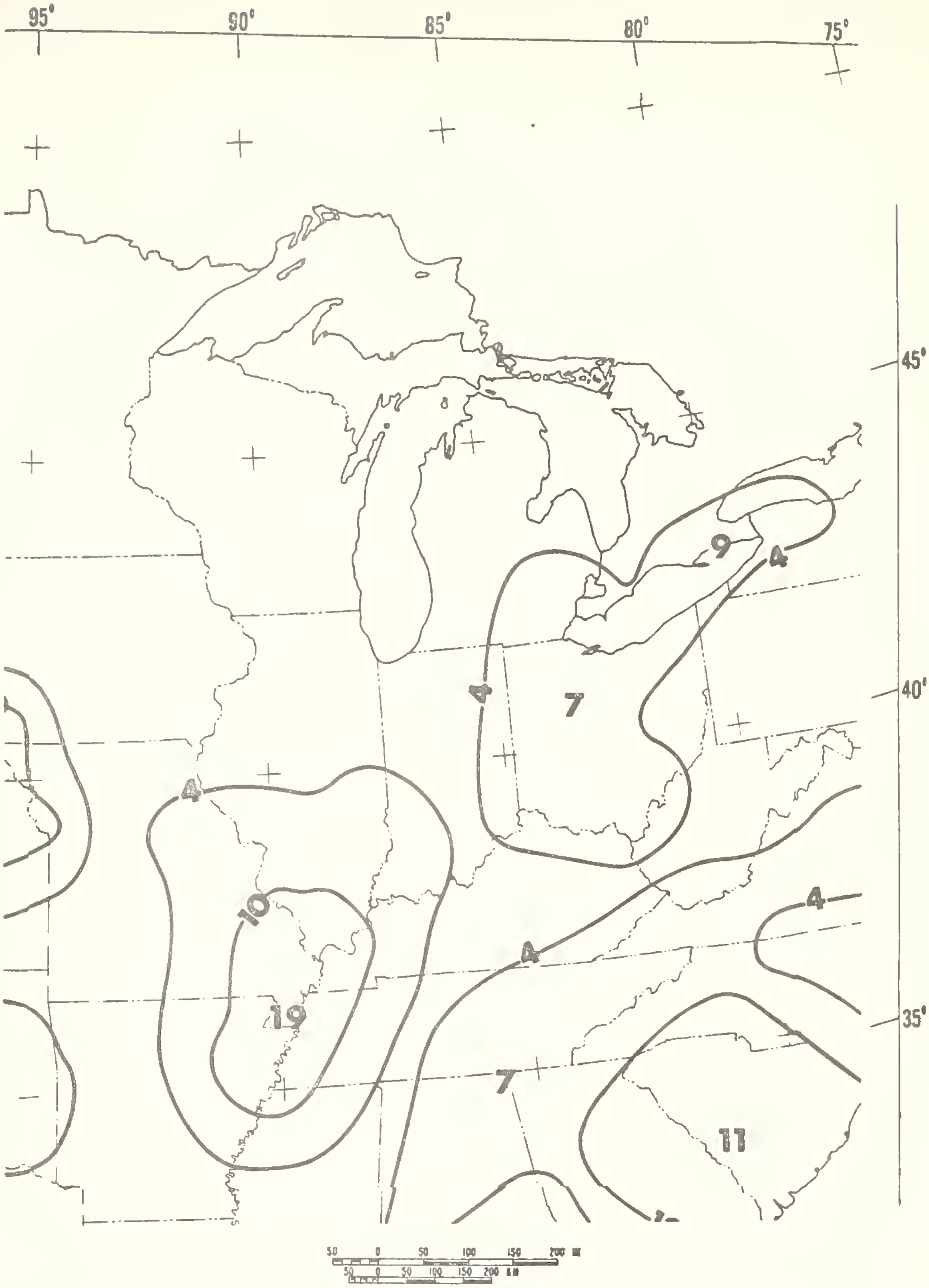


FIGURE 23 PRELIMINARY MAP OF HORIZONTAL ACCELERATION (EXPRESSED AS PERCENT OF GRAVITY) IN ROCK WITH 90 % PROBABILITY OF NOT BEING EXCEEDED IN 50 YEARS.
(ALGERMISSEN & PERKINS, 1976)

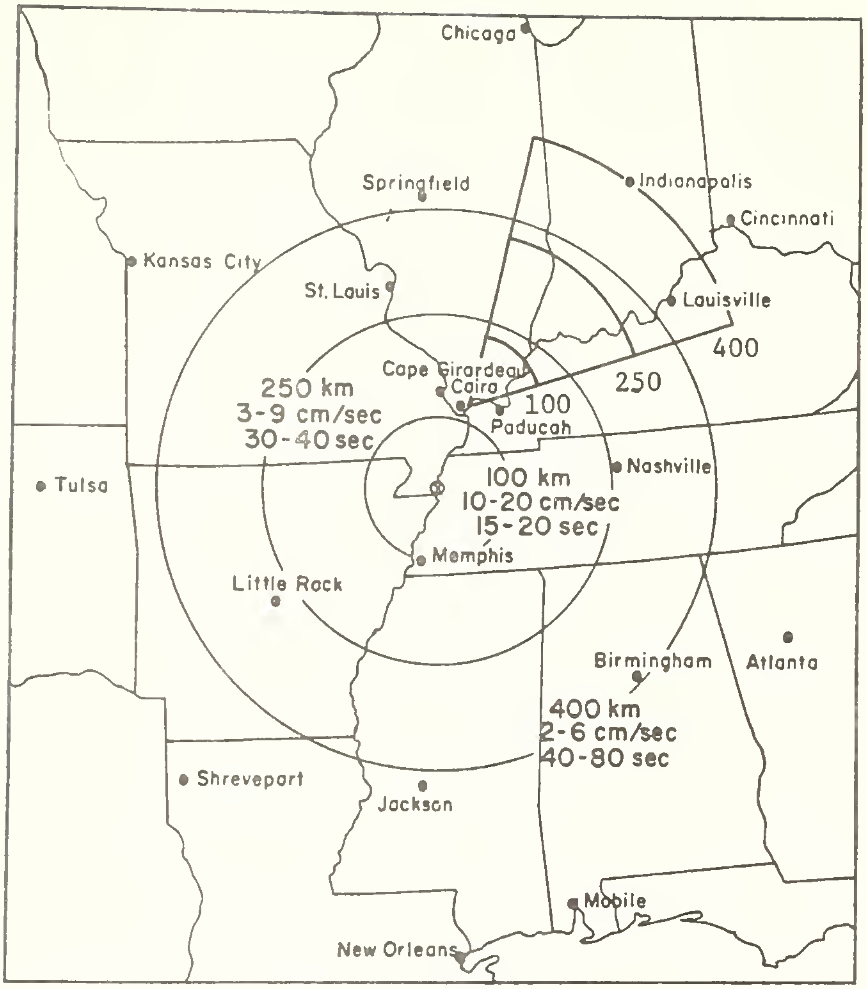


FIGURE 24 ESTIMATED GROUND VELOCITY AND DURATION TIME OF LONGER PERIOD SURFACE WAVE MOTION FOR A MAJOR EARTHQUAKE OCCURRING IN SOUTHEAST MISSOURI. (MODIFIED AFTER NUTTLI, 1974a)

for the 100, 250, and 400 km (62, 156, and 250 miles, respectively) epicential distances. It can be seen in this hypothetical case, that the City of Indianapolis could undergo a ground (hard rock) velocity of 2 to 6 cm/sec. (The threshold of damage is considered to be 5 cm/sec); the resulting ground motion could last 40 to 80 seconds!

In order to examine earthquake effects throughout the State of Indiana, it is convenient to use predictions of ground motion expressed in terms of ground particle displacement, velocity, and acceleration. Nuttli (1973a and 1974a) has examined intensity fall-off in terms of particle velocity which he says correlates best with Intensity. Using Nuttli's velocity fall-off data, contours of maximum particle velocity are plotted for the several events being considered, in Figures 25 through 28.

The contours of (ground) particle velocity on hard rock shown in Figure 25 are identical to those shown in the upper right portion of Figure 24. The contours on Figure 25 represent a more critical situation than the circles of Figure 24 as the epicenter of the Source 1 earthquake has been moved northeasterly approximately 65 miles to Cairo, Illinois. This would represent an even more critical seismic situation. Continued studies of the source mechanisms of midwest earthquakes need to be completed before definitive statements can be made regarding future earthquake epicenters.

Duration of Shaking

Estimated earthquake durations are also shown on Figure 25. The duration of shaking is difficult to predict because of the dearth of

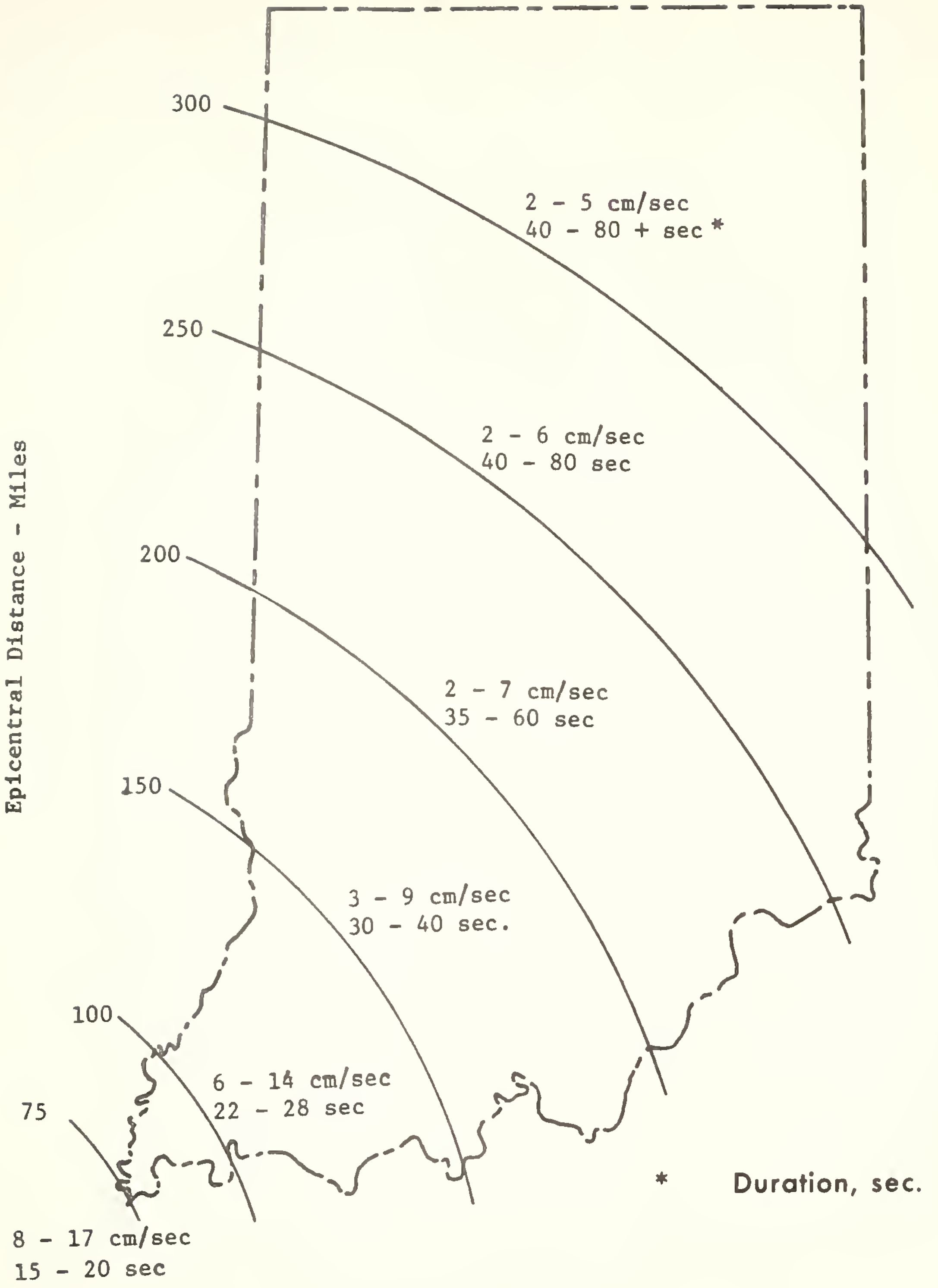


FIGURE 25 PARTICLE VELOCITY FALL-OFF DATA FOR A NEW MADRID SEISMIC ZONE EARTHQUAKE WITH EPICENTER MOVED NORTH TO CAIRO, ILLINOIS. SOURCE 1 EVENT IN ROCK.

data for the midwest, and lack of fundamental understanding of earthquake mechanisms. Krinitzsky (1972), based on the work of Nuttli, gave the following estimates of duration for earthquakes in the midwest:

Source	Body Wave Magnitude	Duration (seconds)
1	7.2	160
2,3	6.2	68
4	5.7	40

Predominant Period of Ground Motion

The predominant period of the earthquake waves is a function of both size and epicentral distance. High frequency body waves attenuate rapidly with distance from the epicenter. Distant shocks, therefore, would tend to have long period waves predominating. Nearby earthquakes (such as design event number 4) would result in high frequency waves predominating. This is significant in design since structures can be strongly affected by earthquake waves with a period close to the natural period of the structure. This will be discussed later in Part III. Nuttli (1974b) states that surface wave ground motion (longer period), exceeds body wave ground motion except at small distances (100 km or less).

The "ground" response data presented in Figures 25 through 28 are for the underlying bed rock. The actual ground surface motion will vary depending on the thickness of the soil layer(s) as well as the shear strength of the soil layer(s) (void ratio for relative density for sands and the undrained shear strength for clays). Nuttli (1973a) states that as a rule of thumb soils can increase the ground surface displacements by a factor of 4 to 5 ground particle by a factor of 2 to 3, in ground data for the midwest, and [illegible]

quake mechanisms, [illegible]

gave the following estimates [illegible]

midwest:

Source [illegible]

1

2,3

4

Prediction

The [illegible]

both [illegible]

[illegible]

would [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

for the [illegible]

depending [illegible]

strength of [illegible]

and the [illegible]

as a rule of thumb [illegible]

by a factor of [illegible]

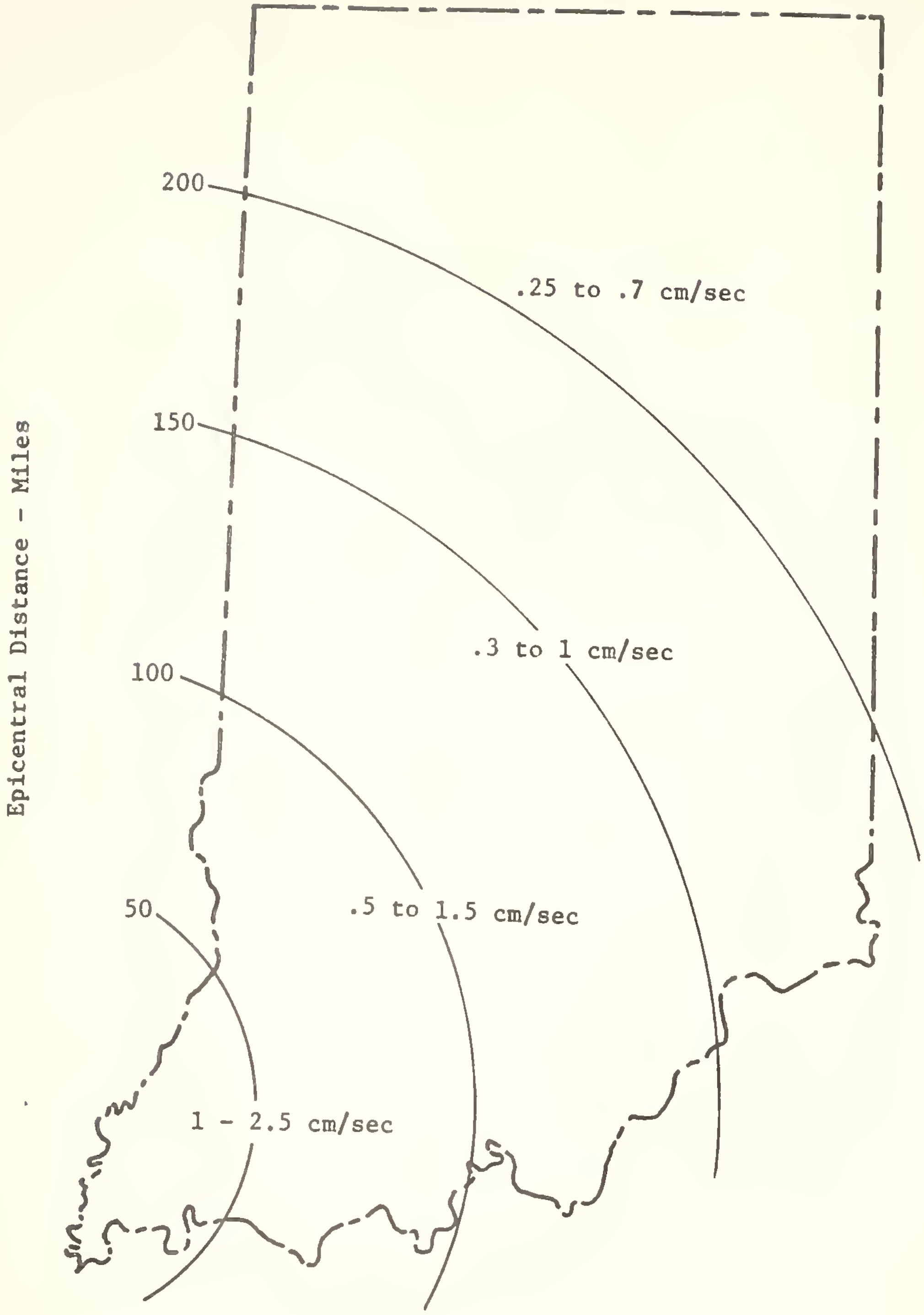


FIGURE 26 PARTICLE VELOCITY FALL-OFF DATA FOR A WABASH RIVER FAULT ZONE EARTHQUAKE. SOURCE 2 EVENT IN ROCK.

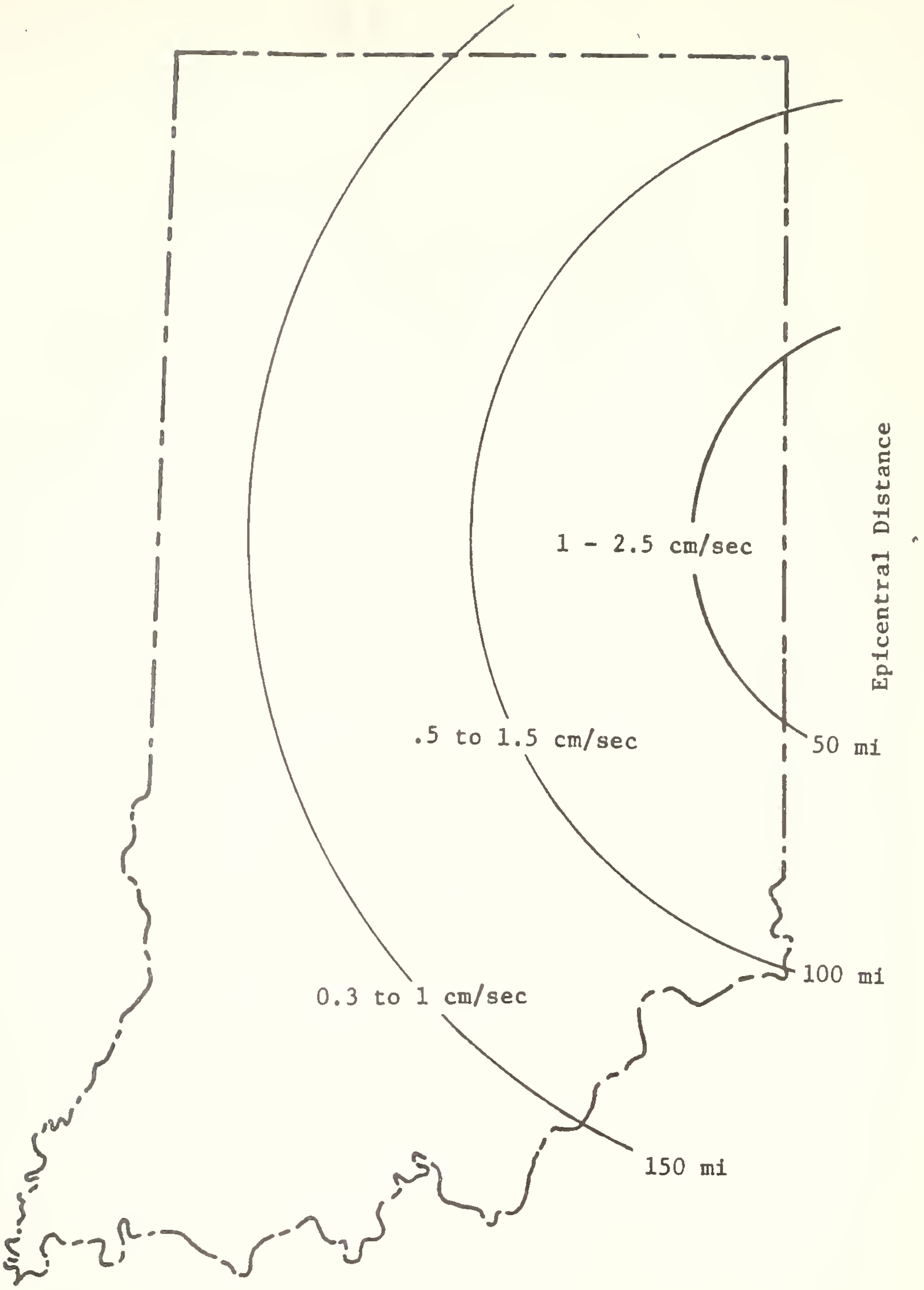


FIGURE 27 PARTICLE VELOCITY FALL-OFF DATA FOR A WESTERN OHIO EARTHQUAKE. SOURCE 3 EVENT IN ROCK.

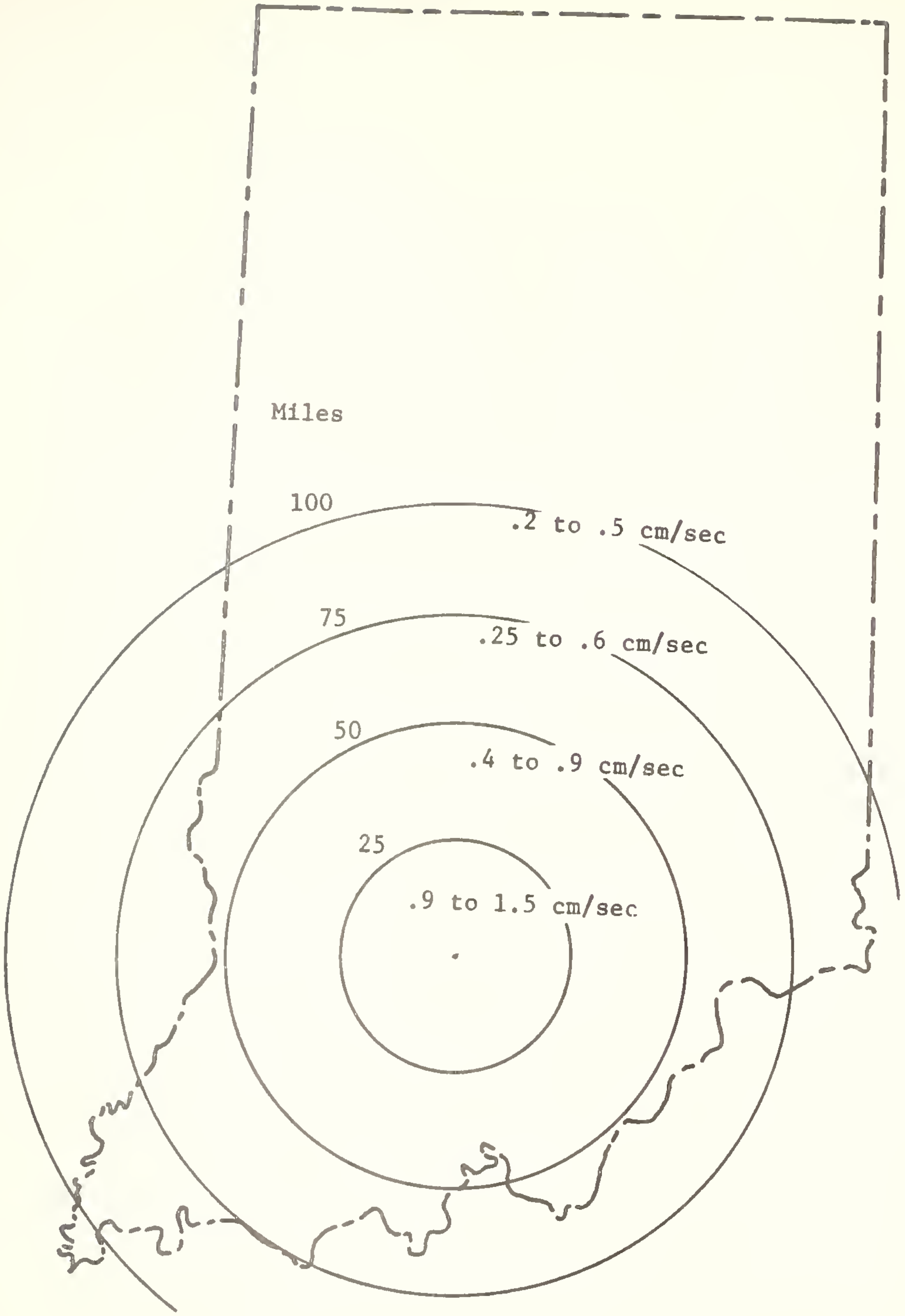


FIGURE 28 PARTICLE VELOCITY FALL-OFF DATA FOR AN INDIANA 'FLOATING' EARTHQUAKE FOR A SOURCE 4 EVENT IN ROCK.

(surface) accelerations by about 1 to 1.5. Detailed response analysis for several typical sites for Evansville, Indiana will be presented in Part III of this study.

Particle velocity fall-off data for the Source 2 earthquake is presented in Figure 26. The epicenter is shown outside of the State of Indiana. Its location is approximate and it is possible for the Source 2 earthquake epicenter to be within a 25 ± mile radius of the location shown. The expected earthquake duration would be less than those shown on Figure 25 for the same epicentral distances.

Similar contours are presented for the Source 3 earthquake with its epicenter in western Ohio. Here also, the epicenter could be expected to move north or south of its shown location. The effect would be to have the contours shown translating north or south of their present position.

Finally, the velocity fall-off data for the Source 4 earthquake which could occur anywhere in Indiana but more likely in the southern part of the state, is presented in Figure 28. Again, these values are for the underlying rock motion and the actual surface motion (acceleration, velocity and displacement) would generally be larger.

Again, recall that these are maximum values and that no expected frequency of occurrence is reflected in Figures 25 through 28. The selection of an appropriate design earthquake level for any given structure would require an analysis of risk. The design earthquake level would have the values shown on Figures 25 through 28 as a probable maximum, but might have a lower value where a risk analysis indicated that some probability of earthquake damage could be tolerated.

Summary

The material presented above is the present state-of-the-art Both the frequency and occurrence of midwest earthquakes given in Task 4 and the design earthquake parameters given in Task 5 are based on data that are all too insufficient to base definitive engineering decisions upon. However, it is all that is presently available.

Design earthquake parameters presented in Task 6 are given for the underlying bed rock and to be useful to the design professional, response analysis for important structures must be made for those individual sites to determine the amount of soil amplification, if any.

Some studies will be presented in Part III of this study specifically for Evansville, Indiana. In the meantime, as present and future research is completed on earthquake sourch mechanisms for the midwest and we experience and study future earthquakes, the information contained in this report should be considered for the seismic design of important structures.

The following tasks of this study will be completed and presented in a later report.

Task No.	Topic
6	Site Response
7	Response Spectra--Time History
8	Microzonation Studies
9	Building Code Seismic Review
10	Specific Conditions--Highways, Bridges
11	Specific Conditions--Buildings

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APPENDIX A

Seismic History

New Madrid Series of Earthquakes

This report would not be complete without a brief account of the New Madrid earthquakes of 1811-1812. From this, hopefully, the reader will gain an appreciation for the potential earthquake hazard in the mid-continent.

The following account is abstracted from Coffman and Von Hake (1973) which is based on the principal historical references to these earthquakes. Some additional information based on the recent work of Nuttli (1973b) has been incorporated.

The three principal shocks in the series occurred on December 16, 1811; January 23, 1812; and February 7, 1812. The total area shaken was at least 2 million square miles, while topographic changes occurred in an area of 30,000 to 50,000 square miles. It is probable that the February 7, 1812 earthquake was the most severe in the series. Each of the principal shocks was followed by many aftershocks of varying intensity. Over 100 aftershocks of moderate to strong intensity, and hundreds of smaller shocks were recorded during the period from December 16, 1811 to March 15, 1812. The aftershock activity lasted throughout at least 2 years.

The Account:

> A little after 02:00 on December 16, the inhabitants of the New Madrid region suddenly were awakened by the groaning, creaking and cracking of the timbers of their houses and cabins, the sounds of furniture being thrown down, and the crashing of falling chimneys.

Landslides swept down the steeper bluffs and hillsides; considerable areas were uplifted; and still larger areas sank and became covered with water emerging from below through fissures or craterlets, or accumulating from the obstruction of the surface drainage. On the Mississippi, great waves were created which overwhelmed many boats and washed others high upon the shore, the returning current breaking off thousands of trees and carrying them into the river. High banks caved and were precipitated into the river; sandbars and points of islands gave way; and whole islands disappeared.

Several persons were drowned when thrown into the river by caving banks, and a number of boatmen were lost when their boats sank. Also, many canoes were seen drifting, their occupants probably having drowned.

In spite of the great intensity of the earthquakes, the loss of life was low. At New Madrid, only one life was lost through falling buildings. Of course, the log cabin, which was the most common type of building at that time, was peculiarly suited to withstand earthquake damage. Chimneys were knocked down, and all the houses were thrown down or badly damaged at New Madrid. The destruction from various causes extended over the entire site of the town, which was consequently abandoned. Chimneys were knocked down in Cincinnati, Ohio, Saint Louis, Missouri, and in many places in Tennessee, Kentucky, and Missouri. Bricks were reported to have fallen from chimneys in Georgia and South Carolina. The shock also was felt strongly in Butler County, Pa.

The shock was felt from Canada to New Orleans, La. and from the headwaters of the Missouri to the Atlantic, including Boston, Massachusetts, 1,100 miles away. Caving of river banks occurred as far away as Vicksburg, Miss. About 1 million square miles or half the area was so shaken that vibrations were distinctly felt. This far exceeds in land area any previous earthquake on this Continent.

The shock of December 16 was felt distinctly in Washington, D.C., and the people were frightened badly. As might be expected, the western parts of the South Atlantic States were shaken more

severely than the eastern parts. The shocks were moderate in the North Atlantic States, being felt at Boston and Baltimore. This is apparently connected with the relation of the Appalachian system to the epicenter of the earthquake. The effect has been noticed to a less degree in the 1886 Charleston, S.C. shock and the 1925 St. Lawrence Valley earthquake. No reliable information about damage or the limit of the area to the west in which the quakes were felt is available because of the sparse population of the western lands at that time.

During December 16 and 17, shocks continued at short intervals but with diminishing intensities. They occurred at longer intervals until January 23 when there was another shock, similar in intensity and destruction to the first. This was followed by 2 weeks of quiescence, but on February 7, there were several alarming and destructive shocks, the last one equaling or surpassing any previous disturbance. For several days the earth was in constant tremor. There is a definite record, kept at Louisville, Ky., that the aftershocks lasted throughout at least 2 years.

Of course, the record is very incomplete, but there is little doubt that the soil was so broken that cultivation at New Madrid and Caruthersville was impossible. The inhabitants feared to rebuild their houses during the period of the severe shocks. There is evidence that the Mississippi Valley was severely and even dangerously shaken in places outside the area of maximum effects.

The most seriously affected area was characterized by raised and sunken lands, fissures, sinks, sand blows, and large landslides. This area was 30,000 to 50,000 square miles in extent, from a point west of Cairo, Ill. to the latitude of Memphis, Tenn., and from Crowleys Ridge to Chickasaw Bluffs, Tenn., a distance of 50 miles.

According to contemporary accounts, waves with visible depressions between the swells rolled across the earth and finally broke open leaving parallel fissures. These were reported to be from 600 to 700 feet long; one had a length of 5 miles. Another wave of smaller size resulted from the settling and caving of river banks.

There was also another type of fissure which consisted of a long, narrow block that dropped and left a trench with vertical sides. Both types have been filled with sand, so their validity is not solely dependent on contemporary accounts. In some places, the fissures were very close together, around 10 to 15 feet apart. Those near rivers were parallel to their courses. Others are usually northeast-southwest. Simple fissures ran up to 300 feet in length; others were considerably greater. The block fissures averaged 300 to 500 feet, with others much longer. The depths were from 10 to 20 feet--the depth to quicksand below. Very few objects were lost in the fissures, though there was considerable fear of being engulfed.

There is some evidence of vertical faults, one of which is believed to have caused quite marked falls in the river, that lasted until the slope had been leveled off. Landslides occurred wherever the river banks were steep and where there were steep bluffs. In places, sections of forests were carried down or overthrown by the slides; many were split. In some cases, trees were thrown over to a sharp angle, beginning to grow in their new positions when the slide came to rest, with the lower parts of the trunks inclined and the upper parts vertical. In other areas, the vibration alone threw down trees.

Several sections were raised 15 to 20 feet above the level of the highest floods. One of these areas, known as Tiptonville Dome, is 15 miles long by 5 to 8 miles wide. There is another area about 10 miles in diameter with an uplift of 10 to 15 feet.

Large areas dropped by amounts reaching 15 feet in some cases, though 5 to 8 feet was more common. In eastern Arkansas, Lake St. Francis, so formed, is 40 miles long by a half mile wide.

The cumulative effects of the earthquake destroyed forests over an area of 150,000 acres. The most typical sunken land of the area is Reelfoot Lake in Tennessee. This lake is 8 to 10 miles in length and 2 to 3 miles in width. The submergence ranged from 5 to perhaps 20 feet, although greater depths were reported.

Ejection of water, sand, mud, and gas were noticeable features of the quake.

Sand blows were very common. Normally, these were nearly circular, 8 to 15 feet across and 3 to 6 inches high. Some reached 100 feet in diameter and the linear varieties were as much as 200 feet long and 50 feet wide. The sand was white, in contrast to the black alluvial soil above. All of the sand blows had craterlike depressions in the middle. They occured frequently throughout an area of 1,400 square miles.

Sand sloughs were also found, depressions of 3 to 5 feet, and were characterized by low, ill-defined ridges of sand parallel to the trend of the depression. Water collected in these, forming long, narrow pools.

Water waves of considerable size were generated on the Mississippi. Starting from different points, they met and caused a sharp wall-like chop. Fissures opened and closed below the surface, sending out waves. Local uplifts and waves moving upstream gave the appearance of the river flowing upstream. Ponds also were noticeably agitated during the shock.

Caving of banks, disappearance of islands, lifting of snags, and floating trees brought into the river by landslides made navigation precarious for some time.

Several earth sounds accompanied the earthquake. The emission of water was accompanied by a hissing and whistling sound. Noises like the discharge of a cannon, the rumbling of distant thunder, and the sound of a carriage passing through the street were heard.

A tabulation of over 500 earthquakes for the study region follows.

(36°-44°N, 81°-91°W)

	DATE		LOCAL TIME			EPICENTER			MODIFIED MERCALLI	RICHTER	PERCEPTIBLE	
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N LAT.	W LONG.	INTENSITY	MAGNITUDE	AREA (Sq. mi.)	REFERENCE
1776	Summer		08	00		Muskingum River, Ohio						1
1779	--					Northern Kentucky						1
1791 or 1792	April or May		07	00		Northern and Eastern Kentucky						1
1795	Jan.	8	03	00		Kaskaskia, Illinois						1
1804	Aug.	24	14	10		Fort Dearborn (Chicago), Illinois	42.0	87.8			30,000	1
1811	Dec.	16	02	00		New Madrid, Missouri	36.6	89.6	X-XII		2,000,000	1,7
1812	Jan.	23				New Madrid, Missouri	36.6	89.6	IX-XII		2,000,000	1,7
	Feb.	7				New Madrid, Missouri	36.6	89.6	X-XII		2,000,000	1,7
1820	Nov.	9	16	00		Cape Girardeau, Mo.	37.3	89.5	IV-V			1
1827	Aug.	6	22	30		New Albany, Indiana	38.3	85.8	VI			1
	Aug.	7	01	00		New Albany, Indiana	38.3	85.8	VI			1
1834	Nov.	20	13	40		Northern Kentucky			V			1,6
1838	June	9	08	45		St. Louis, Missouri	38.5	89	VII-VIII			1,6
1841	Dec.	27	23	50		Near Hickman, Ky.	36.6	89.2	V			1,6
1842	May	27					36.6	89.2	IV			6
1842	Nov	4					36.6	89.2	V			6
	Nov.	4					36.6	89.2	V			6
1843	June	13					36.6	89.2	III			6
1844	Nov.	28	07	00		Knoxville, Tenn.	36.0	84.0	VI			1
1846	Mar.	26					36.6	89.6	III			6
1848	Jan.	24					36.6	89.2	III-IV			6
1850	Apr.	4					38.3	85.8	IV			6

	DATE		LOCAL TIME			EPICENTER			MODIFIED MERCALLI	RICHTER	PERCEPTIBLE	
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W LONG.	INTENSITY	MAGNITUDE	AREA (Sq. mi.)	REFERENCE
1853	Aug.	28					36.6	89.2	III			6
1853	Dec.	18					36.6	89.2	IV-V			6
1855	May	2					37.0	89.2	IV			6
1855	May	3					37.0	89.2	III			6
1856	Nov.	9					36.6	89.5	IV			6
1857	Feb.	-					36.6	89.5	IV			6
1857	Oct.	8	04 04	00 07		St. Louis, Mo.	38.7	89.2	VII		7,500	1,6
1858	Sept.	21					36.5	89.2	VI			6
1860	Aug.	7					37.8	87.5	V			6
1865	Aug.	17	09	00		Southeastern Missouri	36.0	89.5	VII		24,000	1,6
1865	Sept.	7					36.6	89.5	III-IV			6
1868	Nov.	21					36.6	89.2	III			6
1870	Dec.	14					36.6	89.2	III-IV			6
1871	July	21					37.0	89.2	III			6
1871	July	25					38.5	90.0	III			6
1872	Feb.	6	08	00		Wenona, Mich.	43.5	83.8	V		Local	1
1872	Feb.	8					37.0	89.2	III-IV			6
1872	Mar.	26					37.1	88.6	III			6
1873	May	3					36.0	89.6	IV			6
1874	July	9					37.0	89.2	III-IV			6
1875	June	18	07	43		Western Ohio	40.2	84.0	VII		40.000	1
1875	Oct.	7					36.1	89.6	III-IV			6
1876	Sept.	24					38.5	87.8	VI			6
1876	Sept.	25	00	15		Near Evansville, Ind.	38.5	87.7	VI		60,000	1
1876	Sept.	26					38.5	87.8	III			6

	DATE		LOCAL TIME			EPICENTER			MODIFIED MERCALLI	RICHTER	PERCEPTIBLE	
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N LAT.	W LONG.	INTENSITY	MAGNITUDE	AREA (Sq. mi.)	REFERENCE
1877	May	26					38.2	87.9	III-IV			6
1877	July	15					37.7	89.2	III-IV			6
1877	July	15					36.5	89.7	III-IV			6
1877	Aug.	17	10	50		Southeastern Michigan	42.3	83.3	IV-V		200	1
1877	Nov.	19					37.0	89.2	III-IV			6
1878	Jan.	8					37.0	89.2	III-IV			6
1878	Mar.	12	04	00		Columbus, Ky.	36.8	89.1	V		Local	1,6
1878	Nov.	18	23	52		Southeastern Missouri	36.7	89.3	VI		150,000	1,6
1878	Nov.	19					37.0	89.2	III			6
1879	July	26					37.0	89.2	II-III			6
1882	Feb.	9	14	00		Ohio			V			1
1882	July	20	04	00		Southern Illinois	36.9	89.2	V		3,000	1,6
1882	July	28					37.6	90.6	III-IV			6
1882	Sept.	27	04	20		Southern Illinois	39	89.5	VI		40,000	1,6
1882	Oct.	15	00 05	00 00		Southern Illinois	39	89.5	V		40,000	1,6
1882	Oct.	22					38.9	89.4	III			6
1882	Nov.	15					38.6	90.2	III			6
1883	Jan.	10					37.4	89.3	III			6
1883	Jan.	11	01	12		Cairo, Illinois	37.0	89.2	V-VI		80,000	1,6
1883	Feb.	4	05	00		Kalamazoo, Mich.	42.3	85.6	VI		8,000	1
1883	Apr.	12	02	30		Cairo, Illinois	37.0	89.2	VI-VII		Local	1,6
1883	July	6					37.0	89.2	III			6
1883	July	14					37.0	89.2	IV-V			6
1883	Nov.	14					38.7	90.2	IV			6

DATE			LOCAL TIME			EPICENTER			MODIFIED MERCALLI	RICHTER	PERCEPTIBLE	
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1883	Dec.	5					36.3	91.2	V			6
1884	Feb.	15					37.7	90.7	III			6
1884	Sept.	19	14	14		Near Columbus, Ohio	40.7	84.1	VI		125,000	1
1885	Aug.	6	07	00		Watauga County, N.C.	36.2	81.6	IV-V		Local	1
1886	Mar.	1					39.0	85.5	III-IV			6
1886	Mar.	17					37.6	89.2	II-III			6
1886	Mar.	18					37.0	89.2	III-IV			6
1886	Aug.	13					39.7	86.1	III-IV			6
1887	Feb.	6	16	15		Vincennes, Ind.	38.7	87.5	V-VI		75,000	1,6
1887	Aug.	2	12	36		Cairo, Illinois	37.0	89.2	V		Widespread	1,6
1891	July	26	20	28		Evansville, Ind.	37.9	87.5	V-VI			1,6
1871	Sept.	26	22	55		Near Cairo, Ill.	37.0	89.2	V			1,6
1895	Oct.	17					36.6	89.5	III			6
1895	Oct.	18					36.6	89.5	III			6
1895	Oct.	30	3 shocks				36.4	90.6	III			6
1895	Oct.	31	05	08		Charleston, Mo.	37.0	89.4	IX		1,000,000	1,6
1895	Nov.	1					37.0	89.4	IV			
1895	Nov.	2	2 shocks				37.0	89.4	III-IV			
1894	Nov.	17					37.0	89.4	III-IV			
1897	Apr.	30	22	00		Tenn., Ill., Ind., Ky.	37	89	IV			1,6
1897	Oct.	21	21	20		Southwestern Virginia	37	81	V		20,000	1
1898	June	14					36.0	89.4	IV			6
1898	Nov.	25	14	00		Southwestern Virginia			V		65,000	1
1899	Apr.	29	20	05		SW Indiana, SE Illinois	38.5	87.0	VI-VII		40,000	1,6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1899	Feb.	13	03	30		Southwestern Virginia	37	81	V		30,000	1
1901	Feb.	14					36.0	90.0	IV			6
1901	May	17	01	00		Ohio	39.3	82.5	V		7,000	1
1902	Jan.	24	04	48		Missouri	38.6	90.2	VI		40,000	1,6
1902	Mar.	10	2 shocks				39.9	85.2	III-IV			6
1903	Jan.	1	2 shocks				39.9	85.2	II-III			6
1903	Feb.	8	18	21		St. Louis, Mo.	37.8	89.3	VI		70,000	1
1903	Mar.	17					39.1	89.5	III-IV			6
1903	Sept.	20					39.4	86.3	IV			6
1903	Sept.	21					38.7	88.1	IV			6
1903	Oct.	4					37	90	V-VI			6
1903	Nov.	3					37.8	89.3	III-IV			6
1903	Nov.	4	12 13	18 14		St. Louis, Mo.	36.9	89.3	VI-VII		70,000	1,6
1903	Nov.	20					39.4	86.3	III			6
1903	Nov.	24					36.6	89.5	III			6
1903	Nov.	25					36.6	89.5	II-III			6
1903	Nov.	27	03	20		New Madrid, Mo. (2 shocks)	36.5	89.5	V		70,000	1,6
1903	Dec.	11					39.1	88.5	II			6
1905	Aug.	21	23	08		Mississippi Valley	36.8	89.6	VI-VII		40,000	1,6
1906	May	8					39.5	85.8	III-IV			6
1906	May	9					39.2	85.9	IV			6
1906	May	11	00	15		Southwestern Indiana	38.5	87.2	IV-V		800	1,6
1906	May	21	13	00		Flora, Ill.	38.7	88.4	V			1,6
1906	June	27	16	10		Fairport, Ohio	41.4	81.6	V		400	1
1906	Aug.	13					39.7	86.8	IV			6
1906	Sept.	7					38.2	87.7	IV			6

DATE			LOCAL TIME			EIPCENTER			MODIFIED MERCALLI INTENSITY	RICHTER MAGNITUDE	PERCEPTIBLE AREA	REFEREMCE	REMARKS
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.					
1907	Jan.	29					39.5	86.6	V			6	
1907	Jan.	30					38.9	89.5	V			6	
1907	July	4	03	00		Farmington, Mo.	37.8	90.4	IV-V		400	1,6	
1907	Dec.	10					38.6	90.2	IV			6	
1908	Sept.	28	13	34		New Madrid, Missouri	36.6	89.6	IV-V		5,000	1,6	
1908	Oct.	27	18	27		Cairo, Ill.	37.0	89.2	IV-V		5,000	1,6	
1908	Dec.	27					36.8	87.5	IV			6	
1908	Dec.	27					37.0	89.0	IV			6	
1908	Dec.	31					37.0	88.9	III			6	
1909	May	26	08	42		Illinois	42.5	89.0	VII		500,000	1	
1909	July	18	22	34		Illinois	40.2	90.0	VII		40,000	1	
1909	Aug.	16	16	45		Southwestern Illinois	38.3	90.1	IV			1,6	
1909	Sept.	22	03	45		Ohio Valley	38.7	86.5	V		4,000	1,6	
1909	Sept.	27	03	50		Indiana	39.5	87.4	VII		30,000	1,6,8	
1909	Oct.	22					37.6	90.6	IV			6	
1909	Oct.	23	01	10		Southeastern Missouri	37.0	89.5	V-VI		40,000	1,6	
1909	Oct.	23	03	47		Near Robinson, Ill.	39.0	87.8	V		8,000	1,6	
1911	Feb.	28					38.7	90.3	IV			6	
1912	Jan.	2	10	21		Illinois	41.5	88.5	VI		40,000	1	
1913	Mar.	28	15	50		Near Knoxville, Tenn.	36.2	83.7	VII		2,700	1	
1913	Nov.	11					38.2	85.8	IV			6	
1915	Feb.	5					37.7	88.6	IV			6	
1915	Feb.	18					37.1	89.2	IV			6	
1915	Apr.	15					38.7	88.1	II-III			6	
1915	Apr.	28	17	40		New Madrid-Tiptonville, Missouri	36.5	89.5	IV-V		200	1,6	

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1915	Oct.	26	01	40		Maysfield, Ky.	36.7	88.6	V		Local	1,6
1915	Dec.	7	12	40		Near mouth of Ohio River	36.7	89.1	V-VI		60,000	1,6
1916	Jan.	7					39.1	87.0	III			6
1916	Feb.	7					37.6	88.8	III			6
1916	May	21					36.6	89.5	IV			6
1916	Aug.	24					37.0	89.2	IV			6
1916	Aug.	26	13	36		Western North Carolina	36	81	V		3,800	1
1916	Oct.	19					36.7	88.6	III			6
1916	Dec.	18	23	42		Hickman, Ky.	36.6	89.2	V-VI		Local	1,6
1917	Apr.	9	14	52		Eastern Missouri	38.1	90.2	VI		200,000	1,6
1917	Apr.	9					38.1	90.2	IV			6
1917	May	8					36.8	90.4	III-IV			6
1917	May	8					36.8	90.4	III			6
1917	May	9					36.8	90.4	III			6
1917	June	9					36.8	89.4	IV			6
1918	Feb.	17					37.0	89.2				6
1918	June	21	19	00		Lenoir City, Tenn.	36.1	84.1	V		3,000	1
1918	Oct.	13					36.1	91.0	V			6
1919	Feb.	10					37.8	87.5	III-IV			6
1919	Apr.	8					36.2	91.3	III-IV			6
1919	May	23					36.6	89.2	III			6
1919	May	24					36.6	89.2	III			6
1919	May	25	03	45		Southern Indiana	38.4	87.5	V		18,000	1,6
1919	May	26					36.8	89.2	III			6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1919	May	28					36.6	89.2	III			6
1919	May	28					36.4	89.5	III			6
1919	Nov.	3	14	40		Vicinity of Pocahontas, Ark.	36.3	91.0	IV-V		Local	1,6
1920	Apr.	7					36.3	88.2	II			6
1920	Apr.	30					38.6	89.1	IV			6
1920	May	1	09	15		Missouri	38.5	89.5	IV-V		10,000	1,6
1920	Dec.	24	01	30		Rockwood, Tenn. area	36	85	V		Local	1
1921	Jan.	9					36.4	89.5	IV			6
1921	Feb.	7					37.0	89.2	III			6
1921	Mar.	14					39.5	87.5	IV			6
1921	Mar.	31					37.9	87.8	IV			6
1921	July	15				Near Mendota, Va.	36.6	82.3	VI		Local	1
1921	Sept.	8					38.3	90.1	IV			6
1921	Oct.	1					37.7	88.6	IV			6
1921	Oct.	9				(2 shocks)	38.3	90.1	III			6
1922	Jan.	10					37.9	87.8	IV-V			6
1922	Mar.	22	16 20	30 20		Southern Illinois	37.3	88.9	V		25,000	1,6
1922	Mar.	23	15	45		Western Kentucky	37.0	88.9	IV-V			1,6
1922	Mar.	28					36.7	90.4	III			6
1922	Mar.	30					36.1	89.6	IV-V			6
1922	Nov.	26					37.8	88.5	VI-VII			6
1923	Mar.	8					38.9	89.4	III-IV			6
1923	May	6					37.0	89.2	III-IV			6
1923	May	15					37.0	89.2	III-IV			6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1923	Nov.	9	22	00		Tallula, Illinois			V			1
1923	Nov.	28					37.5	87.3	III			6
1923	Nov.	29					37.0	89.2	IV			6
1924	Mar.	2	05	18		Kentucky	37.0	89.1	V		15,000	1,6
1924	Apr.	2					37.1	88.6	IV			6
1924	June	6					36.4	89.5	IV-V			6
1925	Jan	27					36.2	91.7	III			6
1925	Mar.	26	22	06		Southwestern Ohio			V			1
1925	Apr.	26	22	05		Indiana	38.3	87.6	VI-VII		100,000	1,6
1925	May	13	06	00		Kentucky	36.7	88.6	IV-V		3,000	1,6
1925	July	13					38.8	90.0	V			6
1925	Sept.	2	05	55		Kentucky	37.8	87.5	V-VI		75,000	1,6
1925	Sept.	20					37.8	87.5	IV			6
1926	Mar.	22					37.8	88.6	IV			6
1926	Apr.	27					36.2	89.0	IV			6
1926	Oct.	3					38.3	87.6	III			6
1926	Oct.	27					36.7	90.4	IV			6
1926	Nov.	5	09	53		Southeastern Ohio	39.1	82.1	VI-VII		350	1
1926	Dec.	13					36.7	89.4	III			6
1926	Dec.	17					36.4	89.5	IV			6
1927	Jan.	31					37.4	89.7	IV			6
1927	Feb.	3					36.7	90.4	IV			6
1927	Apr.	18					36.3	89.5	IV			6
1927	May	7	02	28		Mississippi Valley	35.7	90.6	VII		130,000	1,6

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1927	Aug.	13					36.4	89.5	V			6
1928	Jan.	23	03	19		Mount Carroll, Ill.	42.0	90.0			400	3
1928	Mar.	17					38.6	90.2	II			6
1928	Apr.	15	09	05		Cape Girardeau, Mo.	37.3	89.5	IV			3,6
1928	Apr.	15					36.6	89.5	IV			6
1928	Apr.	23	05	00		Hickman, Ky.	36.5	89.2	IV			3,6
1928	May	31	16	40		New Madrid, Mo.	36.6	89.5	IV			3,6
1928	Sept.	9	15	00		Lorain and Cleveland,O.	41.5	82.0	V		1,500	1
1928	Nov.	2	22	03		Western North Carolina	36.0	82.6	VI		40,000	1
1928	Nov.	10					36.1	91.1	IV			6
1928	Dec.	25					36.1	91.1	IV			6
1929	Feb.	14	14	12		Princeton, Ind.	38.3	87.6	IV			3,6
1929	Feb.	26	2	15		Arcadia, Mo.	37.6	90.6	IV			3,6
1929	Mar.	8	04	06		Bellefontaine, Ohio	40.3	84.2	V		5,000	1,3
1929	May	12	21	50		Tiptonville, Tenn.	36.4	89.5	III			3,6
1930	Jan.	26					36.1	91.1	IV			6
1930	Feb.	25	06	45		Cairo, Ill.	37.0	90.2	III-IV			3,6
1930	Apr.	2	03	39		Caruthersville, Mo.	36.7	89.7	IV			3,6
1930	June	26	15	45		Bellefontaine, Lima and Wapakoneta, Ohio	40.5	84				3
1930	July	10	18	15		Marion, Ohio	40.7	83.2	Slight			3
1930	Aug.	13					36.6	89.5	II			6
1930	Aug.	29	00	27		Blandville and Barlow, Ky. and Cairo, Ill.	37.0	89.1	IV			3,6
1930	Sept.	1	14	30		New Madrid, Mo.	36.6	89.4	V			3,6
1930.	Sept.	3	06 23	00 30		Blandville, Ky.	37.0	88.9	III			3,6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	MERCALLI INTENSITY	RICHTER MAGNITUDE	PERCEPTIBLE AREA	REFERENCE
1930	Sept.	29	15	15		Sidney, Ohio	40.3	84.2				3
1930	Sept.	30	14	40		Ohio	40.3	84.3	VII			1
1930	Sept.	30	17	50		Sidney, Ohio						3
1930	Oct.	16	15	50		Knoxville, Tenn.	36.0	84.0				3
1930	Dec.	23	08	44		St. Louis, Mo.	38.5	90.7	IV			3,6
1931	Jan.	5	20	51		Elliston, Ind.	39.0	87.0	V		500	1,6
1931	Apr.	1					36.9	88.3	III			6
	Apr.	6					36.8	89.0	IV			6
1931	July	18					36.6	89.5	IV			6
1931	Sept.	20	17	04	54	Anna, Ohio	40.4	84.2	VII		40,000	1,2
1930	Oct.	18	15	12		Madison, Wis.			Feeble			3
1930	Nov.	27	03	23		Nashville, Tenn.						3
1930	Dec.	31				Petersburg, Ind.	38.5	87.2	II			3,6
1932	Jan.	21	PM			Akron, Ohio						3
1930	Nov.	22					36.0	90.2	III			6
1933	Jan.	29	05	00		Newberry, Mich.			II			3
1930	Feb.	22	22	20		Sidney, Ohio			III			3
1930	Mar.	11	06 07	48 04		Poplar Bluff, Mo.	36.7	90.4	III-IV			3,6
1930	May	28	09	10		Maysville, Ky.	38.7	83.7	IV-V		600	1,3
1933	July	13					37.9	89.9	III			6
1933	Aug.	3	22	35		St. Marys, Mo.	37.9	89.9	IV			3,6
1933	Oct.	24					37.3	89.5	III			6
1933	Nov.	16	03	29		St. Louis, Mo.	38.6	90.6	IV		Local	3
1933	Dec.	6	23	55		Stoughton, Wis.			III			3
1934	Apr.	17					37.9	89.9	III			6
1934	May	15					37.9	89.9	III-IV			6
1934	July	3	09	11		Hayti, Mo.						3

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1934	Aug.	19	18	47		Rodney, Mo.	36.9	89.2	VI-VII		28,000	1,3,6
1934	Aug.	19	21	37		Cairo, Ill.	37.0	89.2	II-III			3,6
1934	Oct.	29	20	26		Southeastern Illinois	37½	88½	IV		1,500	3,6
1930	Nov.	12	08	45		Rock Island, Ill.	41.5	90.5	V-VI			1,3
1935	Jan.	5	24	40		Davenport, Iowa, Moline, & Rock Island, Ill.						3
1935	July	23	19	28		Tiptonville, Tenn.	36.4	89.5	IV			3,6
1935	Oct.	(mid)	11	15	?	Negaunee, Mich.						3
1935	Oct.	30	22	30		Negaunee, Mich.						3
1936	Jan.	31	01	30		Tiffin, Ohio						3
1936	Feb.	16	23	05		Hayti, Mo.	36.2	89.7	IV		Local	3,6
1936	Aug.	2	16	15	?	Tiptonville, Tenn. and Cairo, Illinois	36.7	89.0	III			3,6
1936	Oct.	20					36.6	89.6	II			6
1936	Oct.	31					36.6	89.6	II			6
1936	Nov.	23					36.6	90.6	II			6
1936	Nov.	25					36.6	90.6	II			6
1936	Dec.	20	16	41		Cape Girardeau, Mo.	37.3	89.5	II			3,6
1937	Jan.	30	02	57		Caruthersville, Mo.	36.2	89.7	III-IV			3,6
1937	Mar.	2	08	47	36	Western Ohio	40.4	84.2	VII		70,000	1,2
1937	Mar.	3	03	50		Ohio			V			1
1937	Mar.	8	23	44	33	Western Ohio	40.4	84.2	VII-VIII	5.5	150,000	1
1937	Mar.	18					37.7	89.9	II-III			6
1937	May	16	18	50		Northeastern Arkansas	36.1	90.6	IV-V		25,000	1,6
1937	June	23	09	44		Tiptonville, Tenn.	36.4	89.5	III			3,6
1937	Aug.	5	15	31		South St. Louis, Mo.	38.7	90.1	III			3,6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.				
1937	Aug.	5	17	12		Granite City, Ill.						3
1937	Oct.	5	16	58		New Madrid, Mo.	36.6	89.5	III			3
1937	Oct.	16	22	25		Cincinnati, Ohio						3
1937	Nov.	17	11	05		Centralia, Ill.	38.6	89.1	V	8,000		1,6
1938	Jan.	16	22	18		Perryville, Mo.	37.7	89.9	III			3,6
1938	Feb.	12	00	27		So. Shore Lake Mich.			IV			3
1938	Mar.	13	AM			Detroit, Mich.			Slight			3
1938	Mar.	16					36.6	89.6	II			6
1938	Mar.	31	04	10		North Carolina, Tenn. boundary			III-IV			3
1938	Sept.	28					36.5	89.9	III			6
1939	Mar.	18	08	03		Jackson Center, Ohio			Slight			3
1939	Apr.	15	11	30		North of New Madrid, Mo.	36.8	89.4	III			3,6
1939	June	17	21	20		West-Central Ohio			IV			3
1939	July	9	06	50		Anna, Ohio			Slight			3
1939	Sept.	19					36.4	89.5	III			6
1939	Nov.	23	09	14	54	Near Griggs, Ill.	38.2	90.1	V	150,000		1,2,3,6
1940	Jan.	8	14	05		Louisville, Ky & Jeffersonville, Ind.	38.3	85.8	III			3,6
1940	Feb.	4	11	33		Cape Girardeau and Commerce, Mo.	37.2	89.5	III			3,6
1940	May	27	02	30		Louisville, Ky.	38.2	85.8	II-III			3,6
1940	May	31	11	00		Akron, Ohio	37.1	88.6	V			3,6
1940	May	31	13	03		Paducah, Ky			Weak			3
1940	June	15	20	30		Near Nankin, Ohio						3
1940	Sept.	19					36.5	89.6	II-III			6
1940	Oct.	10					36.8	89.2	II-III			6

DATE			LOCAL TIME			EPICENTER			MODIFIED MERCALLI INTENSITY	RICHTER MAGNITUDE	PERCEPTIBLE AREA	REFERENCE
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT	W. LONG.				
1940	Nov.	23	15	15		Tiptonville & Memphis, Tenn.	38.2	90.1	VI			3,6
1940	Dec.	24	20	30		Greenville, Tenn.			Light			3
1940	Dec.	25	00	50		Greenville, Tenn.			Moderate			3
1940	Dec.	28	20	30		Evansville, Ind. and Owensboro, Ky.	37.9	87.3	III			3,6
1941	Mar.	4	01	15		Knoxville, Tenn.			Slight			3
1941	Oct.	8	01	51		Blythesville, Ark. and Tiptonville, Tenn.	36.2	89.7	IV-V			3,6
1941	Oct.	21	10	53		Cairo, Ill. and Wickliffe, Ky.	37.0	89.1	IV			3,6
1941	Oct.	26	22	00		Cape Girardeau, Mo.	36.7	89.7	III			3
1941	Nov.	15					38.3	90.2	III			6
1941	Nov.	22					37.3	89.5	II-III			6
1942	Mar.	1	09	43.1		Kewanee, Ill.	$41^{\circ}14'$	$89^{\circ}44'$				3
1942	Mar.	29	07	43.1		Harrisburg & Eldorado, Illinois	37.7	88.6	IV			3,6
1942	Aug.	31	04	28		Cairo, Ill.	37.0	89.2	IV			3,6
1942	Nov.	17	13	18		East St. Louis, Ill.	38.6	90.2	IV			3,6
1942	Nov.	30					36.8	89.7	III			6
1942	Dec.	27				Maplewood, Mo.	38.6	90.3	II-III			3,6
1943	Mar.	8	21	25	24	Lake Erie area	42.2	80.9	IV-V		40,000	1,2,3
1943	Apr.	13					38.3	85.8	IV			6
1943	June	8	14	50		Webster Groves, Mo.	38.6	90.4	III-IV			3,6
1944	Jan.	6	23	18		Brazeau, Cape Girardeau, Jackson, Mo.	37.5	89.7	IV			3,6
1944	Sept.	25	05	37		St. Louis & Webster Groves, Mo. & East St. Louis, Ill.	37.9	90.0	IV			3,6

	DATE		LOCAL TIME			EPICENTER						
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	MODIFIED MERCALLI INTENSITY	RICHTER MAGNITUDE	PERCEPTIBLE AREA	REFERENCE
1944	Nov.	13	06	52		Anna and Botkins, Ohio						3
1944	Dec.	23					36.2	89.7	IV			6
1945	Jan.	15					37.8	90.2	IV			6
1945	Mar.	27	19	46		St. Louis, Mo.	38.6	90.2	III			3,6
1945	May	2					36.5	89.7	IV			6
1945	May	21	01	51		St. Louis, Mo.	38.6	90.2	IV			3,6
1945	Aug.	6					36.4	89.1	III			6
1945	Aug.	6					36.1	89.7	III			6
1945	Sept.	23	00	22		Cairo, Ill.	36.0	89.8	IV			3,6
1945	Oct.	27					36.5	89.5	III			6
1945	Nov.	13	02	21		Cairo, Ill.	37.0	89.2	IV			3,6
1946	Feb.	24	18	52		Centralia, Ill.	38.6	89.1	I V			3,6
1946	May	15	00	10		Marston and Doniphan, Mo.	36.6	90.8	III-IV			3.6
1946	Oct.	7	19	12	02.5	Between Chloride and French Mills, Mo.	37°28'	90°34'	IV-V		3,000	3,6
1946	Nov.	7					38.0	90.7	II-III			6
1947	Jan.	16					37.0	89.2	II-III			6
1947	May	6	15	25		Southeastern Wisconsin			V		3,000	3
1947	June	29	22	23	53	Near St. Louis, Mo.	38.4	90.2	VI		15,000	1,3,6
1947	Aug.	9	20	46.8		South central Michigan	42.0	85.0	VI		50,000	1,3
1947	Dec.	1	02	47	33	Poplar Bluff and New Madrid, Mo.	36°43'	90°38'	IV			3,6
1948	Jan.	5					38.6	89.1	IV-V			6
1948	Feb.	9	18	00		LaFollette, Tenn.			Light			3
1949	Jan.	13	21	50		Western Tennessee	36.4	89.7	V			3,6
1949	June	8					38.1	90.3	III			6

	DATE		LOCAL TIME			EPICENTER			MODIFIED MERCALLI	RICHTER	PERCEPTIBLE	
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1949	Aug.	11	10	32		Clayton, Mo.	38.6	90.3	II-III			3,6
1949	Aug.	13	15	45		Caruthersville, Mo.	36.1	89.7	III			3,6
1949	Aug.	26	before noon			Defiance, Mo.	38.6	90.7	III			3,6
1949	Sept.	17	03	30		Lee County, Va.						3
1950	May	1	09	30		Gideon, Mo.	36.5	89.9	II-III			3,6
1951	Sept.	19	20	38	43	Southwestern Illinois	38.7	89.9	IV			3,6
1951	Dec.	3	01	02		Willoughby, Ohio			IV			3
1952	Jan.	7	16	21	05	East-Central Illinois						3
1952	Feb.	20	16	34	39	Tenn-Missouri Border	36.4	89.5	V			1,3,6
1952	Mar.	16					36.2	89.6	IV			6
1952	May	28	03	54	14	New Madrid, Mo.	36.6	89.7	IV			3,6
1952	June	11	15	20		Johnson City, Tenn.			Slight			3
1952	June	20	03	38	05	Southeastern Ohio	39.7	82.2	VI		10,000	1,2
1952	July	16	17	48	10	Dyersburg, Tenn. (2 shocks)	36.2	89.6	IV VI			1,3,6
1952	Oct.	16				4 shocks	36.0	89.4	II-III IV			6
1952	Oct.	17	22	16	18	Dyersburg, Tenn.			IV			3
1952	Dec.	28	10	59	27	Mississippi County, Mo.	36.7	89.6	III			3,6
1953	Jan.	26	17	18		Finley, Tenn. (3 shocks)	36.0	89.5	II III IV			3,6
1953	Feb.	11	04	50	54	New Madrid, Mo.	36.5	89.5	IV			3,6
1953	Feb.	17	05 18	45 17		Finley, Tenn. (2 shocks)	36.5	89.5	III IV			3,6
1953	Feb.	18	23	05		Finley, Tenn.	36.0	89.5	III-IV			3,6
1953	May	6					37.0	89.2	III			6
1953	May	7	17	32		Crooksville, Ohio			IV			3
1953	May	15					37.0	89.2	III			6

DATE			LOCAL TIME			EPICENTER			MODIFIED MERCALLI			
YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	RICHTER MAGNITUDE	PERCEPTIBLE AREA	REFERENCE
1953	June	11	PM			Toledo, Ohio			IV			3
1953	Sept.	11	12	26	28	Southwestern Illinois	38.8	90.1	VI			1,3,6
1953	Nov.	10	10	00		Knoxville, Tenn.			IV			3
1953	Dec.	30	16	00		Centralia, Ill.	38.6	89.1	IV			3,6
1953	Dec.	31	20	30		Woodland Park, Ky.			IV			3
1954	Jan.	1	21	25		Middlesboro, Ky.	36.6	83.7	VI			1
1954	Jan.	17	01	15		Dyersburg, Tenn.	36.0	89.4	IV			3,6
1954	Jan.	22	Night			Athens & Etowah, Tenn.			V			3
1954	Feb.	2	10	53		Missouri-Arkansas Border	36.7	90.3	V-VI			1,6
1954	Aug.	9		-		Petersburg, Ind.	38.5	87.3	IV			3,6
1955	Jan.	6	14	30		Briston, Tenn.-Virginia			IV			3
1955	Jan.	12	11	25		Blount and Knox Co. Tenn.			IV			3
1955	Jan.	25	13	34		Knoxville, Tenn.	36.0	89.5	V			3,6
1955	Mar.	29	03	02	40	Finley, Tenn.	36.0	89.5	VI			1,3,6
1955	Apr.	9	07	01	24	West of Sparta, Ill.	38.1	89.9	V-VI		20,000	1,2,6
1955	Apr	11	04	50		Harrisburg, Ill.	37.7	88.6	II			3,6
1955	May	26	12	09	23	Southeast Cleveland, O.	41.5	81.7	V		Local	1,3
1955	May	29		--		Ewing, Ill.	38.1	88.9	III-IV			3,6
1955	June	28	19	15	33	Southeast Cleveland, O.	41.5	81.7	V		Local	1,3
1955	Sept.	5	19	45		Finley & Dyersburg, Tenn.	36.0	89.5	V			1,3,6
1955	Sept.	5	20	00		Finley, Tenn.			IV			3
1955	Sept.	24	12	45		Tiptonville, Tenn.	36.4	89.5	IV			3,6
1955	Sept.	28	01	01	42	Virginia-North Carolina Border C			V		1,700	1,3
1955	Dec.	13	01 01	43 56		Dyer County, Tenn. (2 shocks)	36.0	89.5	III V			1,3,6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1956	Jan.	23	23	00		Caruthersville, Mo.	36.1	89.7	II-III			3,6
1956	Jan.	27	06	03	26	West-Central Ohio			V			1,3
1956	Mar.	13	09	05		Fulton County, Ill.			IV			3
1956	July	18	15	30 to 1700		Oostburg, Wis.			IV			3
1956	Sept.	9	15	45		College Grove, Tenn.			IV			3
1956	Oct.	13		-		Milwaukee, Wis.			IV			3
1956	Oct.	29	03	23	44	Caruthersville, Mo.	36.1	89.7	V			1,3,6
1956	Nov.	25	22	12	44	Wayne County, Mo.	37.1	90.6	VI		21,500	1,2,6
1957	Jan.	25	12	15		Noetown, Ky.						3
1957	Mar.	26	02	27	06	Paducah, Ky.	37.1	88.6	IV-V		Local	1,3,6
1957	June	23	00	34	18	East-Central Tenn.	36-1/2	84-1/2	V			1,2
1957	Aug.	17	Late PM			Bogota, Tenn.	36.0	89.5	IV			3,6
1958	Jan.	26					36.1	89.7	V			6
1958	Jan.	27	23	56	40	Ill.-Ky.-Mo. Border	37.1	89.2	V		300	1,3,6
1958	Apr.	8	16	25	33	Obion County, Tenn.	36.3	89.2	V		400	1,3,6
1958	Apr.	26	01	30		Lake County, Tenn.	36.4	89.5	V			1,6
1958	May	1	16	46	31	Cleveland, Ohio	41.5	81.7	V		Local	1,3
1958	Nov.	7	20	41	43	Illinois-Indiana Border	38.4	87.9	VI		33,000	1,2,6
1958	Oct.	22	20	29	47		37.5	82.5				2
1959	Jan.	6	09	07		North St.Louis County,Mo.	38.7	90.3	III			3,6
1959	Jan.	21	09	35		Ridgely, Tenn.	36.3	89.5	IV			3,6
1959	Feb.	13	02	37		Bogota, Tenn.	36.1	89.5	V		170	1,6
1959	June	12	between 1900 and 1930			Tellico Plains, Tenn.			IV		900	3
1959	Dec.	21	10	25		Finley, Tenn.	36.0	89.5	V		400	1,6
1960	Jan.	28	15	38		Dyer County, Tenn.	36.0	89.5	V		Local	1,6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1960	Apr.	15	04	10	10	Eastern Tenn.			V		1,300	3
1960	Apr.	21	04	45		Lake County, Tenn.	36.3	89.5	V		Local	1,6
1960	May	4	10	31	32	Pine Bluff, Ark.			IV			3
1961	Feb.	22	03	45	03	Northwestern Ohio	41.2	83.4	V			1,3
1962	Feb.	2	00	43	34	New Madrid, Mo.	36.5	89.6	VI	4.3	35,000	1,2,3,4,6
1962	Feb.	16					37.0	88.7	III-IV			6
1962	March	25					36.5	89.5		3.2		6
1962	May	24					36.5	89.5		3.0		6
1962	June	26	19	28	55.7	Southern Illinois	37.8	88.9	V	5.38		1,2,6
1962	July	13	20	23	42.6		36.4	89.8				2
1962	July	14					36.9	90.0	II-III			6
1962	July	23	00	05	18.4	Southern Missouri	36.1	89.8	V-VI			1,2,6
1963	Mar.	3	00	30	13.0	Southeastern Missouri	36.7	90.0		4.7	100,000	1,2,3,4,6
1963	Mar.	31					36.5	89.5		3.0		6
1963	Apr.	6	02	12	24		36.4	89.8		3.1		2,6
1963	May	1	19	09	21.7		36.7	89.4		3.1		2,6
1963	July	8					37.0	90.5		3.1		6
1963	Aug.	2	18	37	50.3	Illinois-Kentucky Border	37.0	88.8	V	4.0		1,3,6
1963	Oct.	28	16 19	38 57	35	Near Galax, Va.	36.7	81.0	V		1,300	1,3
1963	Dec.	5	00	51	02.5		37.2	87.0	II-III			2,6
1963	Dec.	14	23	31	32.9	Beechmont, Ky.	37.2	87.1	III			3,6
1964	Jan.	15	23	09	57.8		36.8	89.5		4.5		2
1964	Jan.	20	07	37	52.0	Cane River, N.C. area			IV			3
1964	Mar.	16	20	15		Caruthersville, Mo.	36.2	89.6	IV	3.5		3,6
1964	May	23	05	25	34.2		36.5	89.9	IV-V	4.0		2,6
1964	May	23	09	00	35.2		36.5	89.9	III	3.5		2,6

YEAR	DATE MO.	DAY	LOCAL TIME HR.	MIN.	SEC.	EPICENTER LOCATION	EPICENTER N. LAT.	EPICENTER W. LONG.	MODIFIED MERCALLI INTENSITY	RICHTER MAGNITUDE	PERCEPTIBLE AREA	REFERENCE
1964	July	28	early afternoon			Knoxville, Tenn.			Light			3
1964	Oct.	13	10	30		Knoxville, Tenn.			Light			3
1964	Nov.	24	20	50	05		37.4	81.5		4.5		2
1965	Feb.	10	21	40	24.3		36.4	89.7		3.5		2,6
1965	Mar.	25	06	59	28.1	New Madrid, Mo. region	36.4	89.5	III	3.7		2,3,6
1965	Mar.	26					36.5	89.5		3.1		6
1965	Apr.	26	09	26	21.5		37.3	81.6				2
1965	May	25					36.5	89.5		3.3		6
1965	June	1					36.5	89.5		3.3		6
1965	July	8					36.5	89.5		3.5		6
1965	Aug.	13	23	04	30.1		37.1	89.3				2
1965	Aug.	13	23	46	17.8	Southwestern Illinois	37.3	89.5	IV	3.2	80	2,3,4,6
1965	Aug.	14	07	13	56.6	Southwestern Illinois	37.1	89.2	VII	3.8	300	1,2,4,6
1965	Aug.	15	00 22	07 19	25.3 00.3	Southwestern Illinois	37.4	89.5	V	3.5		1,2,3,6
1966	Feb.	13	17	19	36.9		37.1	91.0	IV	4.7		2,6
1966	Feb.	13	18	08	55.9	Covington, Tenn.	37.1	91.0				2,3,6
1966	Feb.	26	02	10	20		37.2	91.0		3.8		2,6
1966	Mar.	13					36.5	89.5		3.1		6
1966	June	22					38	89		3.2		6
1966	Aug.	24	00	00		Eastern Tennessee			IV			3
1967	Feb.	2	00	30		Lansing, Mich.			IV			3
1967	Feb.	12					36.0	90.0		3.1		6
1967	Apr.	7	23	40	32.3	Columbus, Ohio	39.6	82.5	V	4.5	4,000	1,2,3
1967	Apr.	11					36.5	89.5		3.0		6
1967	July	6					36.5	89.5		3.3		6
1967	July	21	03	14	48.9	Southeastern Missouri	37.5	90.4		4.3	21,000	1,2,3,4,6

YEAR	DATE MO.	DATE DAY	LOCAL TIME HR.	LOCAL TIME MIN.	LOCAL TIME SEC.	LOCATION	N. LAT.	W. LONG.	MODIFIED MERCALLI INTENSITY	RICHTER MAGNITUDE	PERCEPTIBLE AREA	REFERENCE
1967	Aug.	5	06	37	31.5	Missouri	38.3	90.6		2.8	600	3,4
1967	Oct.	18					36.5	89.5		3.1		6
1967	Dec.	16	06	23	37.4		37.4	81.6		3.5		2
1968	Jan.	23					36.5	89.5		3.3		6
1968	Feb.	9	19	34	32.1	New Madrid, Mo. region	36.5	89.9	III	3.5		2.6
1968	Mar.	31	11	58	09		38.0	89.7		3.5		2,4,6
1968	May	29					36.5	89.5		3.2		6
1968	July	14					36.5	89.5		3.1		6
1968	Nov.	9	11	01	42.0	South central Illinois	38.0	88.5	VII	5.5	580,000	1,2,4,6
1968	Nov.	9					38.0	88.5		3.0		6
1968	Nov.	9					38.0	88.5		3.8		6
1968	Dec.	11	9	00		Louisville, Ky.	38.2	85.9	V	4.2		1,3,6
1969	Jan.	20	13	25		Fredericktown, Mo.	37.7	90.5	III	3.2		2,6
1969	Feb.	28					37.9	88.9		3.2		6
1969	July	13	15	51	09.4	Eastern Tennessee	36.1	83.7	V	3.5	20,000	2,3
1969	July	14	05	15		Knoxville, Tenn.						3
1969	July	24	12	10		Knoxville, Tenn			III			3
1969	July	27					36.5	89.5		3.1		6
1969	Nov.	19	19	00	09	Southern West Virginia	37.4	81.0	VI	4.8	100,000	1,2
1970	Jan.	7	11	45		Millington-Raleigh, Tenn.			IV			3
1970	Feb,	5				(3 shocks)	37.9	90.6	II	3.0 3.2 3.4		6
1970	Mar.	26	20	44	29.5	New Madrid, Mo. region	36.5	89.7	III	3.5		2,6

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YEAR	MO.	DAY	HR.	MIN.	SEC.	LOCATION	N. LAT.	W. LONG.	INTENSITY	MAGNITUDE	AREA	REFERENCE
1970	July	6	03	39	10.7	Eastern Missouri	37.9	90.6	III	3.4		2,6
1970	July	30	02	48	51.5		37.0	82.2		3.8		2
1970	July	30	09	15	16.3		37.0	82.2		4.0		2
1970		11	00	14	25.5	West Virginia	38.4	82.3	IV			2
1970	Sept.	9	19	41	10	Northwestern North Carolina	36.1	81.4	V		2,000	1,2
1970	Nov.	5					36	90		3.0		6
1970	Nov.	16	20	13	55.1	Arkansas	35.9	90.1	V-VI	4.4	30,000	2,6
1970	Nov.	29	22	46	53		36.3	89.5	III-IV	3.7		4,6
1970	Dec.	8					36	89		3.0		6
1970	Dec.	24	04	17	56	New Madrid, Mo. region	36.7	89.5	IV	3.6	1,600	2,4,6
1971	Feb.	12	06	44	27.7	Southern Illinois	38.5	87.9	IV	3.3	3,900	2,4,3,6
1971	Feb.	19	17	11	41.7		37.1	83.2				2
1971	Mar.	31	23	05	11		37.4	81.6				2
1971	July	12	21	03		Eastern Tennessee			V		2,000	3
1971	Oct.	18					36.7	89.6		3.0		6
1972	Jan.	9	17	24	29.1		37.4	81.6				2
1972	Jan.	31	23	42	10.5	Northoast Arkansas	36.4	90.8	V	3.9	10,500	2,4,3
1972	Feb.	1					36.4	90.8	V-VI	4.2		6
1972	Mar.	29	14	38	31.9	New Madrid, Mo. area	36.2	89.6	V	3.7	65,800	2,6,3
1972	May	20	13	39	06.4		37.0	82.2				2
1972	June	9	13	15	19.1	Eastern Missouri	37.7	90.4	III	3.0	140	2,4,6,3
1972	June	18	23	46	14.7	Cape Girardeau, Mo. region	37.0	89.1	III-IV	3.2	230	2,4,6
1972	June	20	20	31	17		37.1	89.8		2.7		4
1972	Sept.	14	23	22	15.5	Northern Illinois	41.6	89.3	VI	3.7	250,000	2,4,5,3
1972	Dec.	3	a.m.			Auburn, Indiana						3
1976	Apr.	8	02	39		Stinesville, Indiana			V	2.8		9

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Appendix B

Physiographic Units in Indiana

The following physiographic unit descriptions are based on Witczak (1970). See Figure 14 for unit boundaries.

Unit No.	Description
142	Lake Chicago - Lacustrine plain associated with high water phases during Pleistocene glaciation. Lacustrine sediments are primarily very fine textured. Associated with the lacustrine deposits are irregular granular beach deposits marking former levels of the old lake.
143	Kankakee Sand Basin - Basin area filled by water-deposited sands associated with glacial drainage and ponding of several glacial drainage outlets in northern Indiana and Illinois.
155	Eastern Lakes Drift Area - Prominent to gently rolling morainic topography with poorly integrated drainage system developed on Cary and younger type of glacial drift. Bedrock in the form of slightly exposed cuesta areas.
159	Tipton Till Plain - Typical till plain area exhibiting flat to gently undulating terrain developed on Tazewell and older Wisconsin drift.
160	Illinois Drift Area - Drift plain developed on Illinoian drift. Relief within the area is slightly more excessive than that found in the Tipton Till Plain. The depth of the Illinoian drift gradually thins to the south so that the physiography may in part, reflect the character of the underlying bedrock to a greater degree in these areas.

182 Indiana/Kentucky Coal Fields - Maturely dissected upland formed on Pennsylvanian sandstones, shales and clays.

183 Mammoth Cave Plateau - Heavily dissected plateau exhibiting topography somewhat similar to the Kentucky/Indiana Coal Fields unit. The bedrock, however, is primarily complex Mississippian formations of shale, sandstone and limestone.

184 Western Pennyroyal Limestone Plain - Plain formed primarily on Mississippian limestones. Karst topography is prevalent in much of the unit.

185 Knob Hill - This area generally exhibits conical or hilly type of terrain. Bedrock is primarily Mississippian - Devonian in age. Massive shale with sandstone or limestone caps comprise the higher hill portion while shale predominates in the lower hill area.

188 Outer Blue Grass - Gently rolling topography developed on alternating, thinly bedded shales and limestones of upper Ordovician age.

Appendix C

Glossary

ACCELEROGRAM. The record from an accelerometer showing acceleration as a function of time.

AFTERSHOCKS. Minor seismic tremors that may follow an underground nuclear detonation or the secondary tremors following the main shock of an earthquake.

AMPLIFICATION. Frequency dependent modification of the input bedrock ground motion characteristics by the local soil column. Amplification causes the amplitude of the surface ground motion to be increased in some range of frequencies and decreased in others. Amplification is a function of the shear modulus and damping of the soil, its thickness, and its geometry.

AMPLITUDE. Maximum deviation from mean or center line of wave.

ANOMALY. A deviation from uniformity or normality.

ARCHES. An elongated "A" Shaped structure resulting from the horizontal compression of formerly horizontal beds of rock.

ATTENUATION. (1) a decrease of signal magnitude during transmission. (2) a reduction in amplitude or energy without change of waveform. (3) the decrease in seismic signal strength with distance which does not depend on geometrical spreading but may be related to physical characteristics of the transmitting media causing absorption and scattering.

BASEMENT. The igneous, metamorphic or highly folded rock underlying sedimentary units below which there is no current economic interest.

BASIN. A large tectonic depression of the underlying bedrock of the earth's crust. A basin may extend thousands of feet deep in extend from miles to thousands of miles across.

BODY WAVE MAGNITUDE. See magnitude.

BODY WAVES. Waves propagated in the interior of a body, i.e., compression and shear waves, the P and S waves of seismology.

DOME. A three dimensional arch structure where upward vertical movement of the former horizontal beds has occurred. It is the opposite of a basin.

EARTHQUAKE WAVES. Groups of elastic waves propagating in the earth, set up by a transient disturbance of the elastic equilibrium of a portion of the earth.

EPICENTER. The point on the earth surface directly above the point of origin of the earthquake. (See Figure 1 and 2).

EPICENTRAL DISTANCE. The horizontal distance along the earth's surface from the epicenter of an earthquake to any point in question. (See Figure 1 and 2).

FAULTING OR FAULT. The various tectonic plates and crustal blocks are separated by faults. Faults are the great fractures that form lines of weakness in the masses of the rock that make up the earth surfaces. These blocks are elevated tilted, folded, and depressed according to the directions of the stresses that are applied to the different blocks. (See Figure C-1 for further definitions.)

FELT AREA. That special area surrounding the epicenter of an earthquake in which the earthquake is felt by individuals. Outside the felt area, the earthquake is imperceptible.

FOCAL DEPTH. The vertical distance between the hypocenter and the earth's surface (epicenter) in an earthquake (or aftershock).

FOCUS. That point along the fault, within the earth, where rupture begins and from where the earthquake originiates. (See Figure 1).

GEOMORPHIC. The process in which the landforms are established. Such processes include weathering (mechanical, chemical and biological), glaciation, tectonic movements, etc.

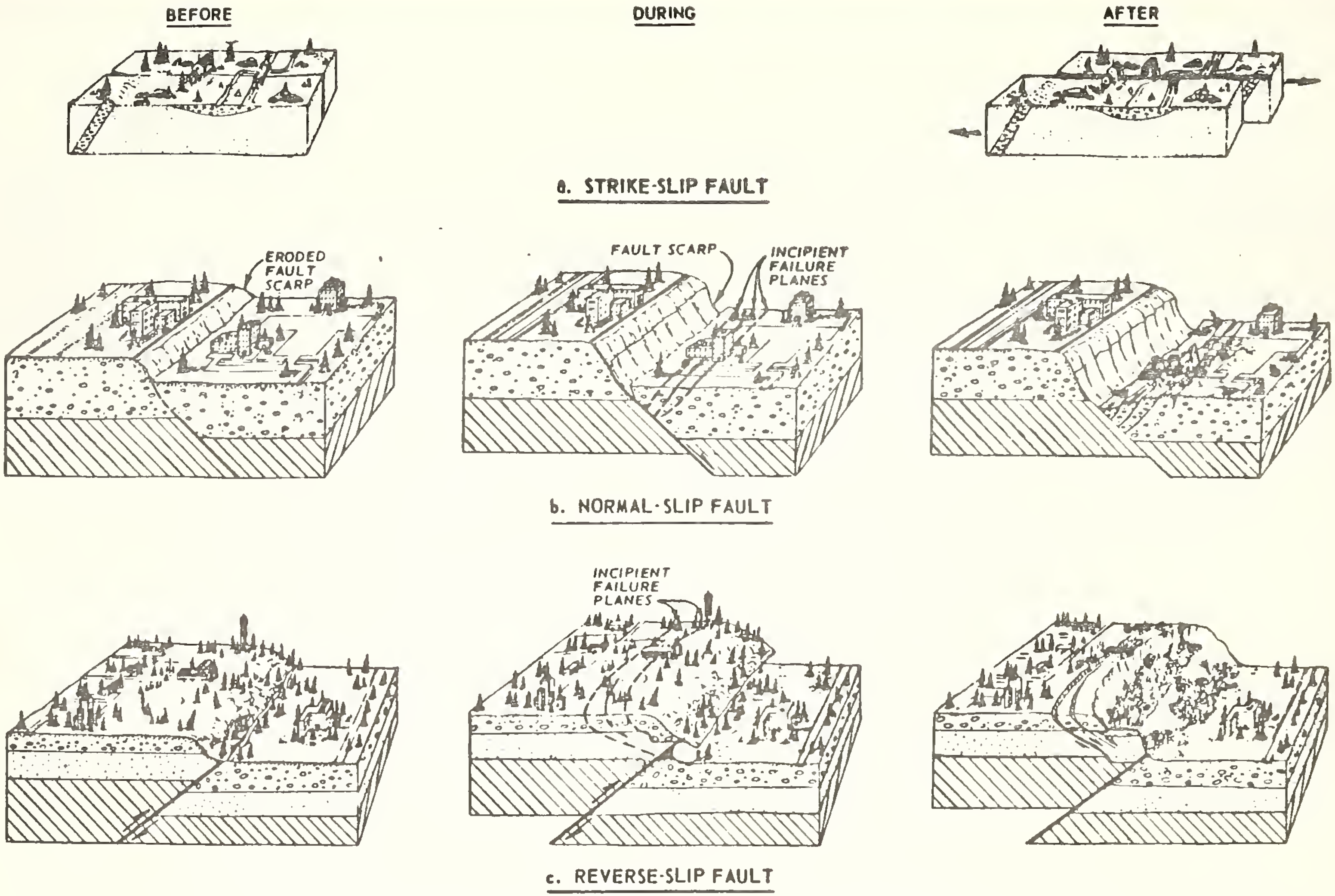
GEOSYNCLINE. Refers to very large depressions (or very large elevations for a geoanticline) in the earth's crust and maybe miles in areal extent. When these terms are used, sometimes it does not necessarily imply that the horizontal beds within the syncline (or anticline) have been once folded or warped due to tectonic stresses.

HYPOCENTER. That point along the fault, within the earth, where rupture begins and from where the earthquake originates. (See Figure 1). Another word for FOCUS.

HYPOCENTRAL DISTANCE. The straight line distance from the focus of the earthquake, through the earth, to any point on the earth's surface. (See Figure 1).

INTENSITY. A numerical index describing the effects of an earthquake on man, on structures built by him and on the earth's surface. The number is rated on the basis of an "earthquake intensity scale", the scale in common use in the U.S. today is the Modified Mercalli Scale of 1931 with grades indicated by Roman numerals from I to XII. The narrative descriptions of each intensity value are given in TABLE 2.

ISOSEISMAL. An isoseismal line is a "contour" line which goes through a series of points on the earth surface that have the same earthquake Intensity. The highest intensity will generally occur near the epicenter of the earthquake. Intensity decreases with increasing distance away from the epicenter. An isoseismal map is shown on page 9.



Surface effects of faulting on strike-slip, normal-slip, and reverse-slip faults before, during, and after displacement (after Cluff et al.[31]). Oblique-slip faults combine strike-slip and normal-slip or reverse-slip components to form normal-oblique-slip or reverse-oblique-slip faults

FIGURE C-1 DEFINITIONS OF FAULT TYPES. (Slemmons, 1977)

LINEAMENT. Although the dictionary defines this word as "one of the outlines, features, or contours of a body or figure", it is understood in this report to refer to an alignment (linear or a smooth curve) of features or events such as the location of epicenters or land forms.

LIQUEFACTION. The sudden large decrease of the shearing resistance of a cohesionless soil. It is caused by a collapse of the structure by cyclic or other type of strain and is associated with a gradual but temporary increase of the pore water pressure. It involves a temporary transformation of the material into a fluid mass.

MAGNITUDE. A quantity characteristic of the total energy released by an earthquake, as contrasted to "intensity", which describes its effects at a particular place. Professor C. F. Richter devised the logarithmic magnitude scale in current use, which is in terms of the motion which would be measured by a standard type of seismograph located 100 kilometers from the epicenter of an earthquake. Several magnitude scales are in use, e.g.; body wave magnitude, surface wave magnitude which utilize body waves and surface waves, respectively. The scale is open ended, but the largest known earthquake magnitudes are near 8.9.

Magnitude values calculated by United States Geologic Survey are based on the following formulae:

For the surface-wave magnitude (M_S):

$$M_S = \log (A/T) + 1.66 \log D + 3.3,$$

as adopted by the International Association of Seismology and Physics of the Earth's Interior, where A is the maximum horizontal surface-wave ground amplitude in micrometers of surface waves having a period T between 18 and 22 seconds, and D is the distance limited to the range of 20 to 160 geocentric degrees (station to epicenter). No depth correction is made for depth less than 50 km.

The body-wave magnitude (m_b) is determined by:

$$m_b = \log (A/T) + Q (D,h),$$

as defined by Gutenberg and Richter (1956), varying from their definition in that T, the period in seconds, is restricted to $0.1 < T < 3.0$, and A, the ground amplitude in micrometers, is not necessarily the maximum of the P-wave group. Q is a function of distance D and depth h, where $D > 5°$.

The local magnitude (M_L) is restricted to distances less than 600 km and is determined by:

$$M_L = \log A - \log A_0,$$

as defined by Richter (1958, p. 340), where A is the maximum trace amplitude, in millimeters, written by a Wood-Anderson torsion seismometer, and $\log A_0$ is a standard value distance function. (Meyers et.al. 1976)

MICROTREMOR. A feeble earth tremor resulting from natural or man-made forces.

MODIFIED MERCALLI INTENSITY SCALE. The first scale developed to indicate the intensity of an earthquake shock was developed in Europe in the 1880's by Rossi and Forel. In 1902, the Italian seismologist, Mercalli set up a new scale based on the range of intensities from I to XII. The Mercalli scale was modified in 1931 by two American seismologists, Wood and Neumann, in order to take into account modern features and construction. Richter abridged the 1931 the version as presented in Table 1 and it is now referred to as "Modified Mercalli Scale, 1956 version", to reflect the abridgement by Richter.

NORMAL FAULT. Vertical movement along a sloping fault surface in which the block above the fault has moved downward relative to the block below. (See Figure C-1)

P WAVE. (See also compression or body wave)-Body wave in which the direction of the particle motion is the same as the direction of wave propagation. Wave velocity is commonly measured in geophysical refraction surveys to define the contact between the dynamic properties of competent rock layers (high velocity materials) and softer or less competent soil layers (low velocity materials).

PERCEPTIBILITY, LIMIT OF. Refers to a distance away from the epicenter of an earthquake where one just perceives the effects of the earthquake. (This is felt motion or some other outward manifestation of energy release.)

PLATE TECTONIC THEORY. A theory which considers that the outer shell of the earth is divided into a number of plates. Major earthquakes occur at these particular boundaries between plates. These plates fit closely together and move around by the Earth's internal forces which extend the plates in some regions of the earth while they destroy the plates in other regions. The outlines of the plates are deduced from the zones at which the earthquakes most frequently occur. Most earthquakes that occur in the United States occur between the American and Pacific plates.

RAYLEIGH WAVE. = R wave: A type of seismic surface wave which propagates along the surface. Particle motion is elliptical and retrograde in the vertical plane containing the direction of propagation and its amplitude decreases exponentially with depth.

RICHTER SCALE. The "local magnitude" scale developed by Richter in 1935 as a measure of earthquake energy release. (See Magnitude)

S WAVE. (Shear Wave) - Body wave in which the particle motion is at right angles to the direction of wave propagation. SH and SV denotes planes of polarization of wave. Wave velocity may be measured by in-hole geophysical procedures to determine the dynamic shear moduli of the materials through which the wave passes.

SEISMOGRAM. A record of ground motion or of the vibrations of a structure caused by a disturbance, such as an underground detonation or an earthquake.

SEISMOGRAPH. An instrument that scribes a permanent continuous record of earth vibrations during an earthquake.

SHEAR WAVE. = S wave = transverse wave: A body wave in which the particle motion is perpendicular to the direction of propagation.

STRIKE. The orientation, projected on the earth's surface, with respect to a reference axis. For example, a line going in the Northeast direction has a strike of North 45° East.

STRIKE-SLIP FAULT. A fault in which movement is principally horizontal. See Figure C-1

SURFACE WAVES. Seismic energy which travels along or near the surface. Includes Rayleigh and Love waves.

SURFACE WAVE MAGNITUDE. See Magnitude.

SYNCLINAL. The downward movement or depression of once formerly horizontal beds of rock. The bottom trough or depression area of the folded rocks are synclinal.

TECTONIC(S). Deformation of rocks by naturally generated stresses due to the constant movement of the various tectonic plates making up the outer shell of the earth.

TECTONIC PROVINCE. As defined by the Nuclear Regulatory Commission, it is a region of the North American continent characterized by the uniformity of the geologic structures contained therein.

TECTONIC STRUCTURE. As defined by the Nuclear Regulatory Commission, it is a large dislocation or distortion within the earth's crust whose extent is measured in miles.

THRUST FAULT. An inclined fracture along which the rocks above the fracture have apparently moved up with respect to those beneath. (See Figure C-1)